

Detection of Multi-Decadal Variability Using GFDL's Coupled Data Assimilation System

**– Part I: 20th Century Ocean Temperature
Observational Network Only**

S. Zhang, Tony Rosati and Matt Harrison
GFDL/NOAA, Princeton University

Ocean Analyses Using Models and Data:

One side: facts -

- § Climate model: inevitable drift from reality due to incomplete understanding of climate change and its modeling
- § Observations: inevitable instrument and representation errors

The other side: we need -

- § Analysis of climate variability (Carbon/heat uptake, circulation, ...)
- § **Detection of climate change**
- § **Observing system evaluation/design**
- § Forecast initialization (SI, decadal)
- § Model evaluation, forecast verification
- § Model parameter estimation

OUTLINE

Can ocean data assimilation detect the signal of climate change?
Are available observations sufficient?

Idealized ‘twin’ experiments: Assimilating samples of the truth

- Climate detection by data assim: ‘to be’ or ‘not to be’?
- Using 20th/21st century obs network: Observing system evaluation

A ‘super-parallelized’ ensemble filter with the GFDL’s coupled climate model (CM2)

- Ocean Data Assimilation (ODA) tests importance of maintaining the T-S relation
- Atmosphere Data Assimilation (ADA) tests importance of maintaining geostrophic balance

25-year results on climate detection using 20th century ocean temperature observational network

Discussions and future directions

OUTLINE

Can ocean data assimilation detect the signal of climate change?
Are available observations sufficient?

Idealized ‘twin’ experiments: Assimilating samples of the truth

- Climate detection by data assim: ‘to be’ or ‘not to be’?
- Using 20th/21st century obs network: Observing system evaluation

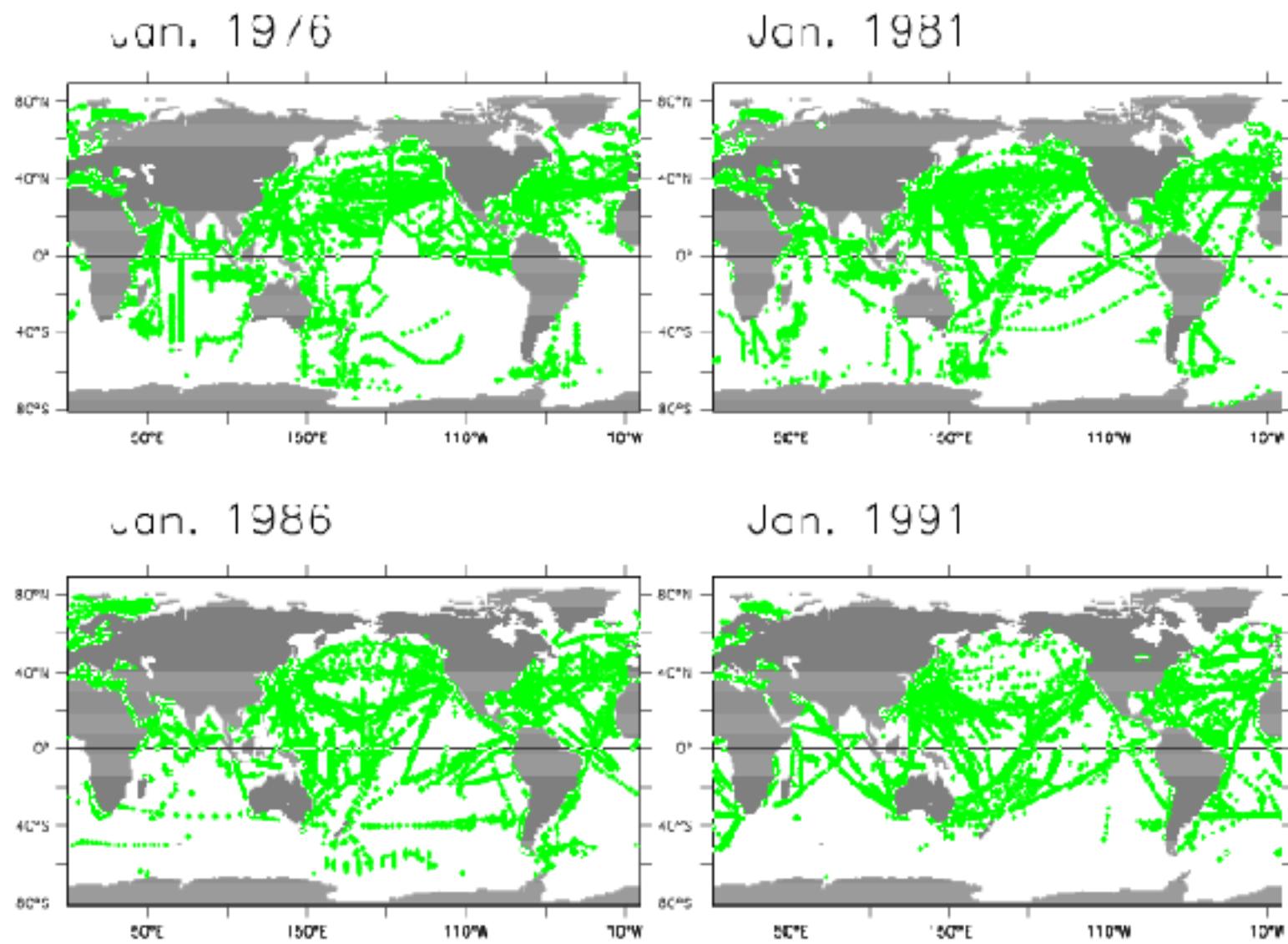
A ‘super-parallelized’ ensemble filter with the GFDL’s coupled climate model (CM2)

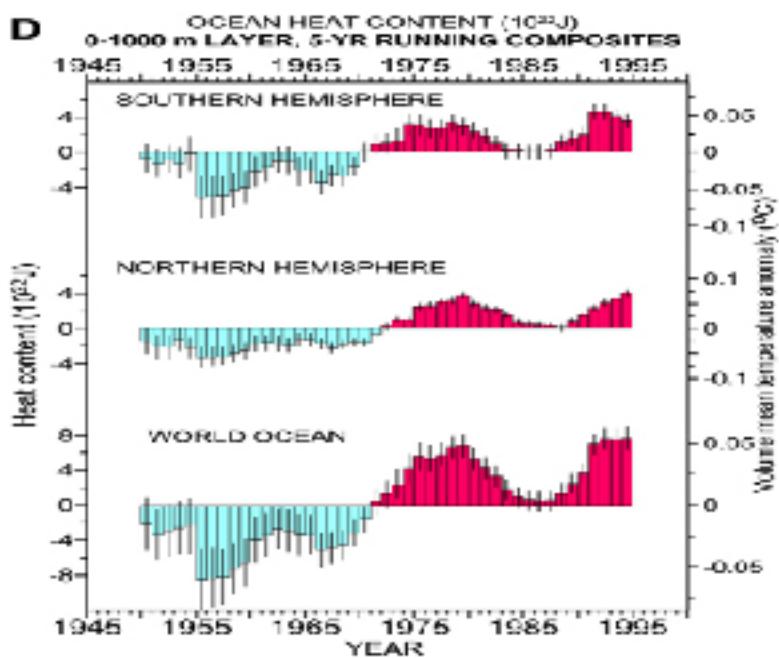
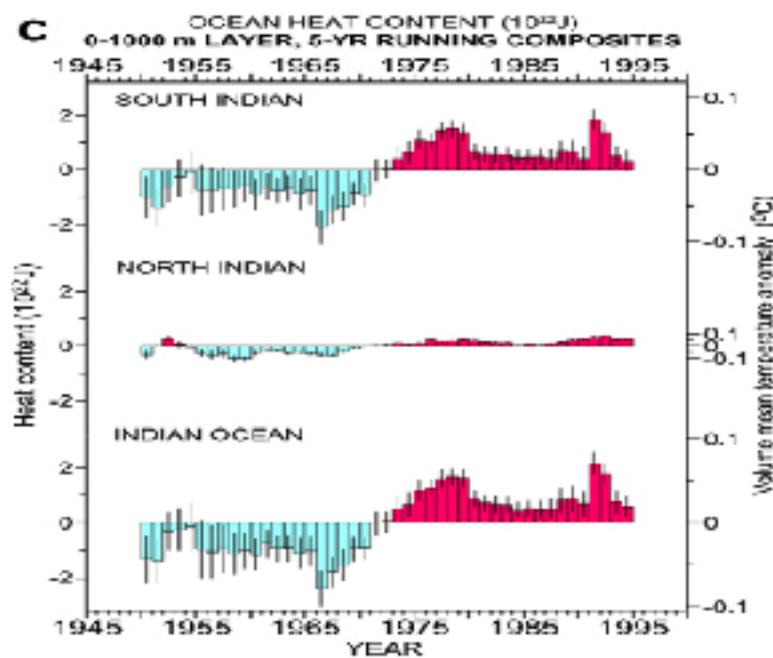
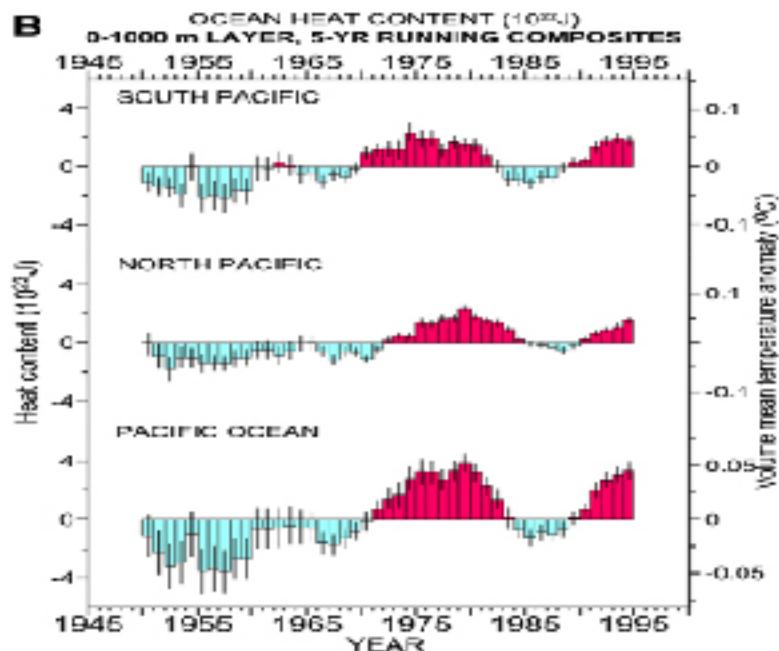
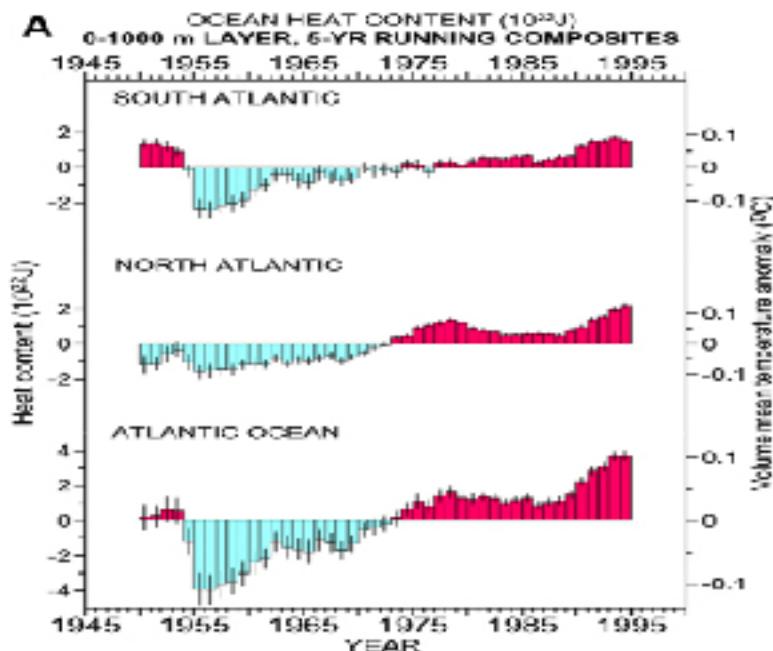
- Ocean Data Assimilation (ODA) tests importance of maintaining the T-S relation
- Atmosphere Data Assimilation (ADA) tests importance of maintaining geostrophic balance

25-year results on climate detection using 20th century ocean temperature observational network

Discussions and future directions

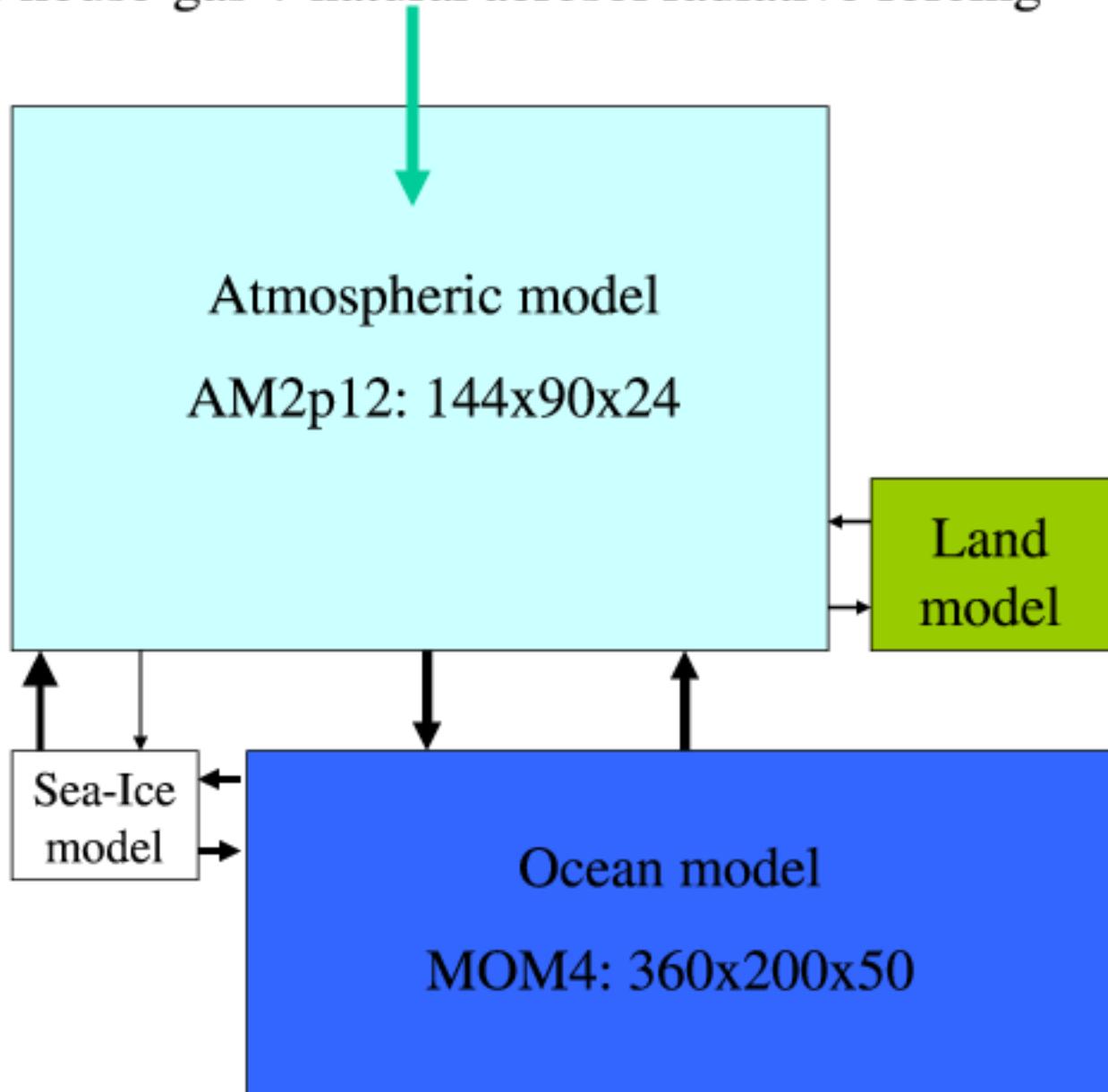
Given ocean temperature observational network
Can we assess climate change in the 20th Century?





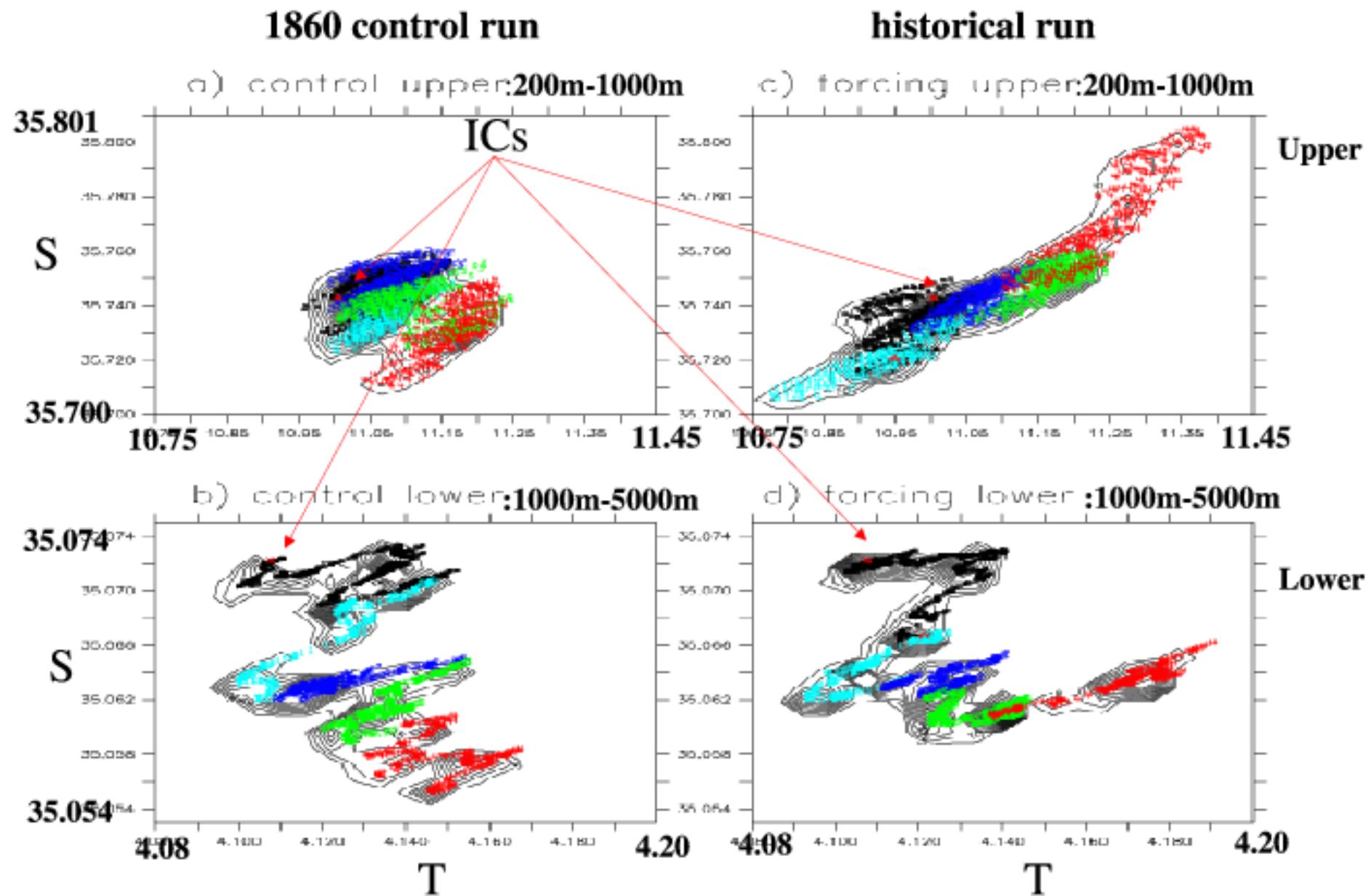
(Levitus et al. 2001)

green-house-gas + natural aerosol radiative forcing



1861-1900
 1901-1925
 1926-1950
 1951-1975
 1976-2000

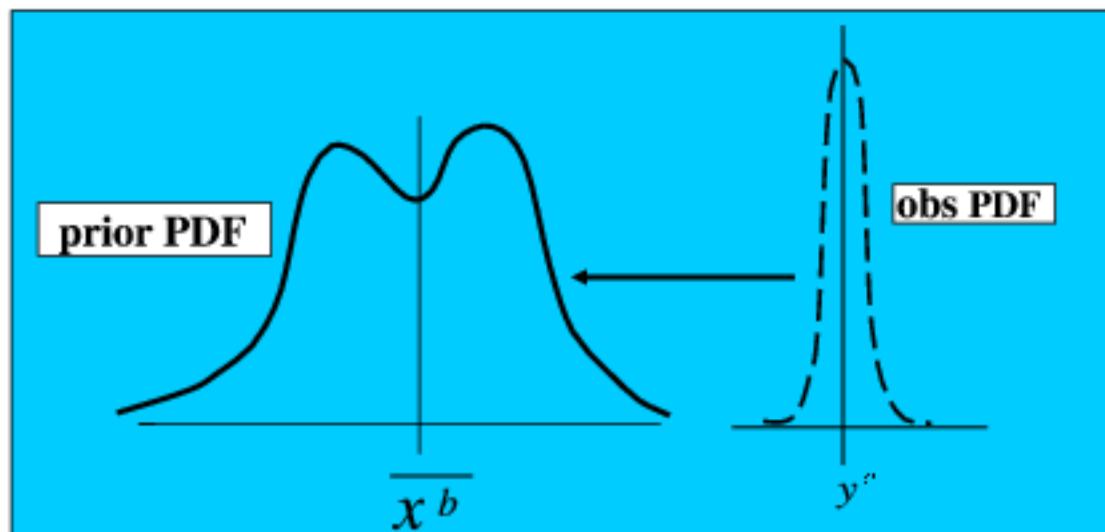
North Atlantic Temp and Salt in CM2



Deterministic (being modeled)

$$\frac{d\mathbf{x}_t}{dt} = f(\mathbf{x}_t, t) + \mathbf{G}(\mathbf{x}_t, t)\mathbf{w}_t$$

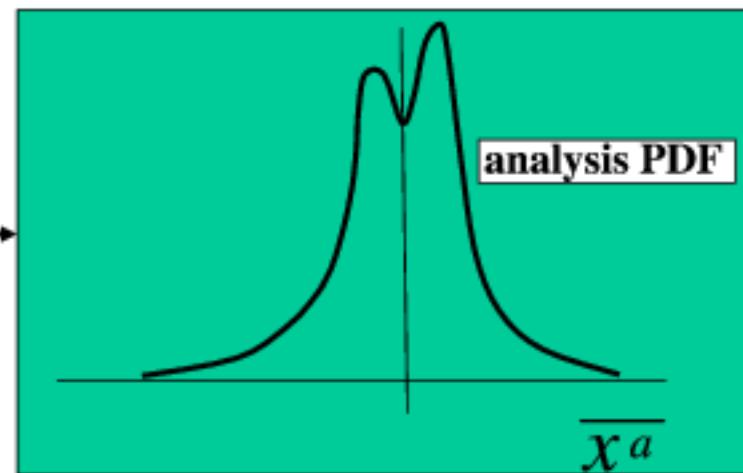
Uncertain (stochastic)



Atmospheric
internal
variability

Ocean internal
variability
(model does not
resolve)

Data
Assimilation
(Filtering)



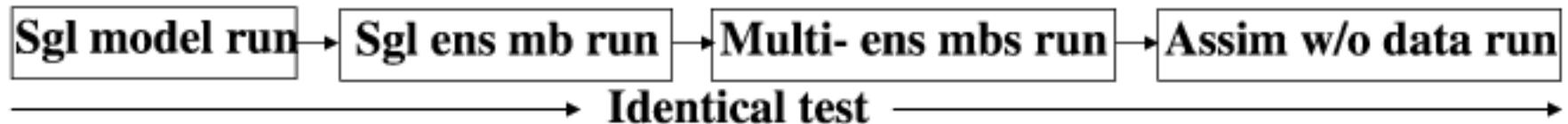
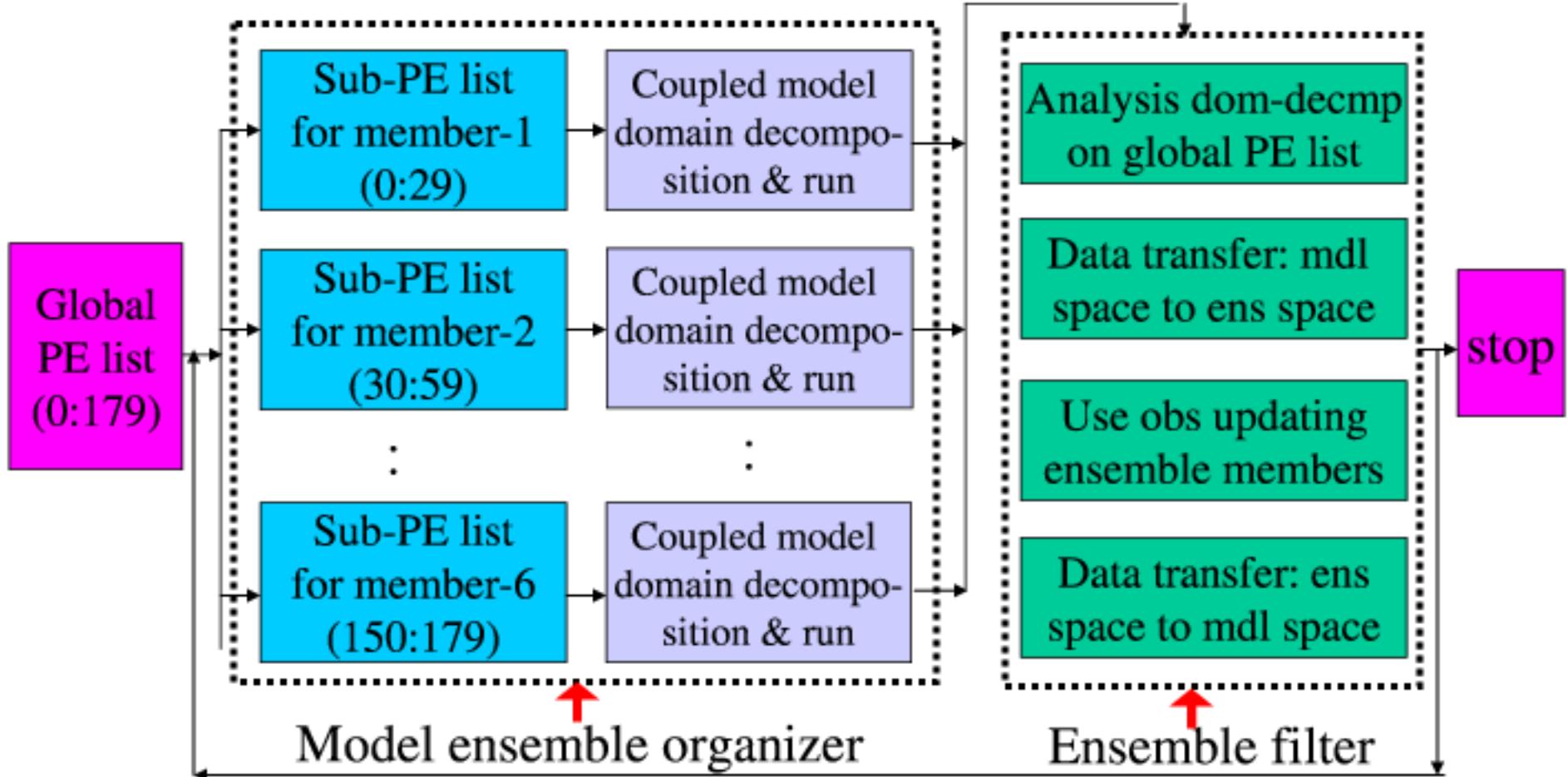
Accessing Climate Change Using Models and Data: Solving a temporally-evolving *Joint-distribution* on state variables

Estimating a temporally-evolving *joint-distribution* requires:

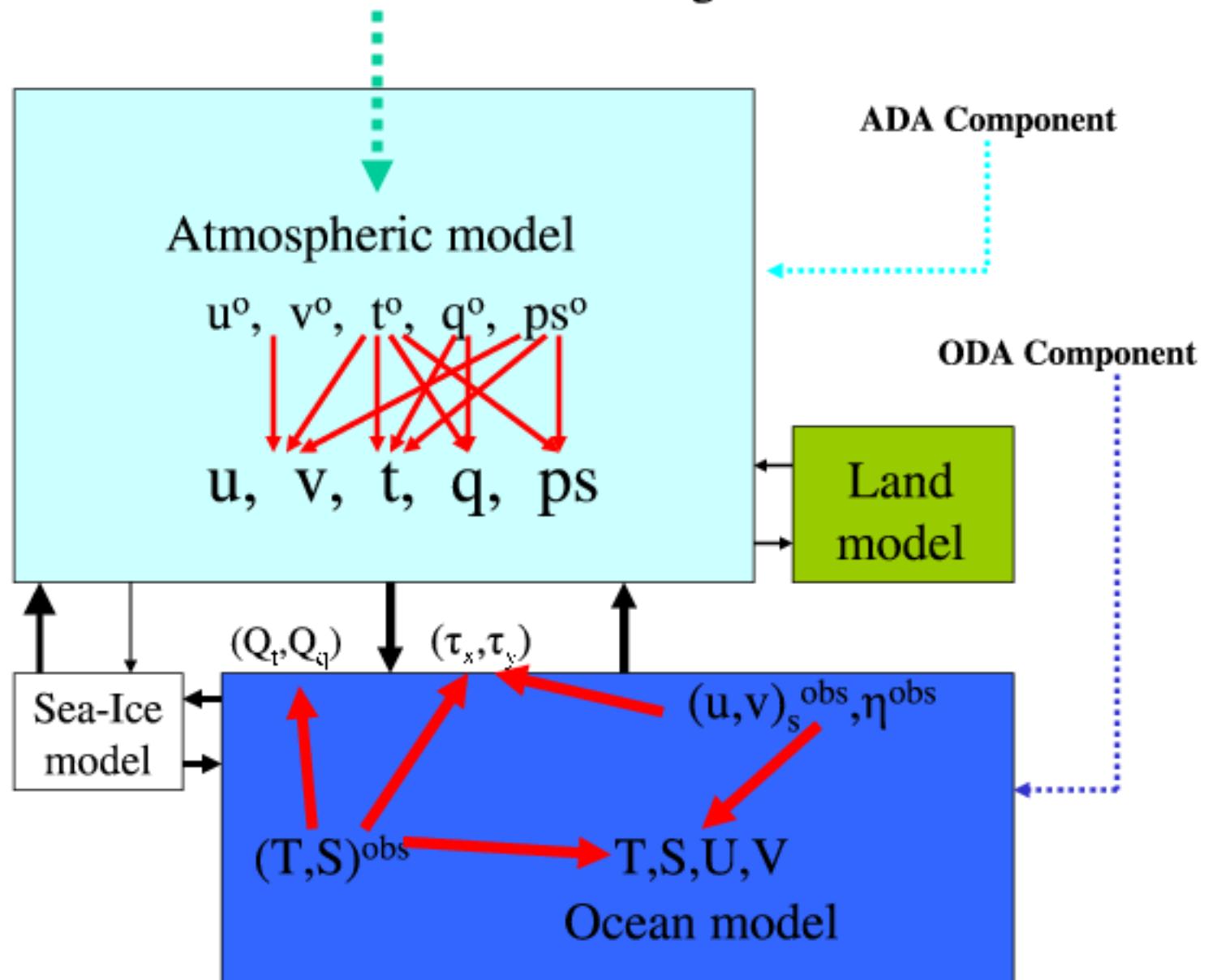
- Maintain physical balances among state variables
- Maintain the properties of high order moments of error statistics (nonlinear evolution of errors)

An ensemble filter maintains the above two properties at most by imposing the observational PDF onto the prior PDF for updating the ensemble (Zhang and Anderson 2003)

CM2 ensemble filter: PE grouping and domain decomposition



GHG + NA radiative forcing

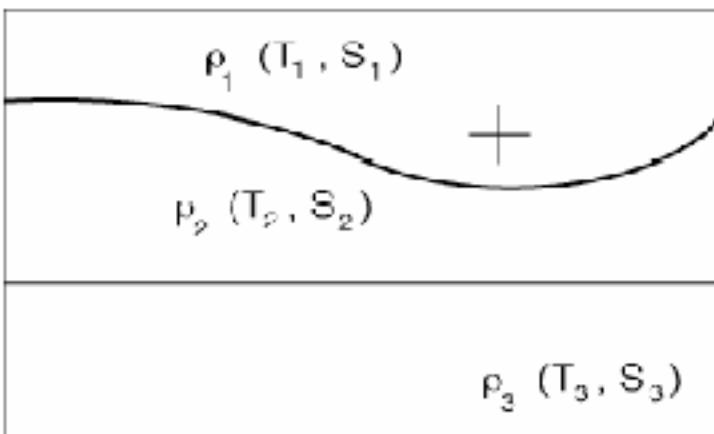
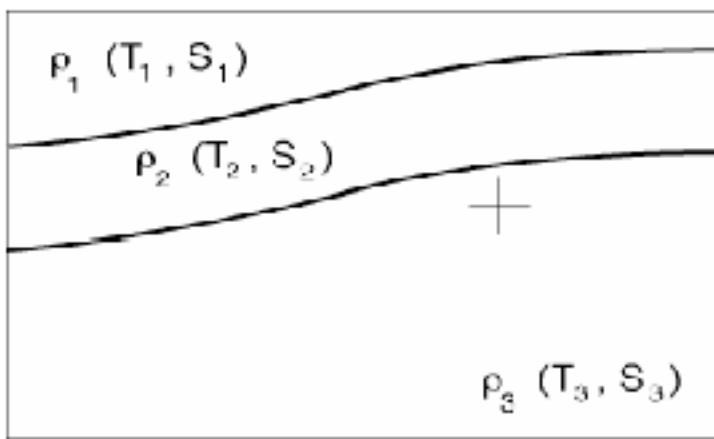
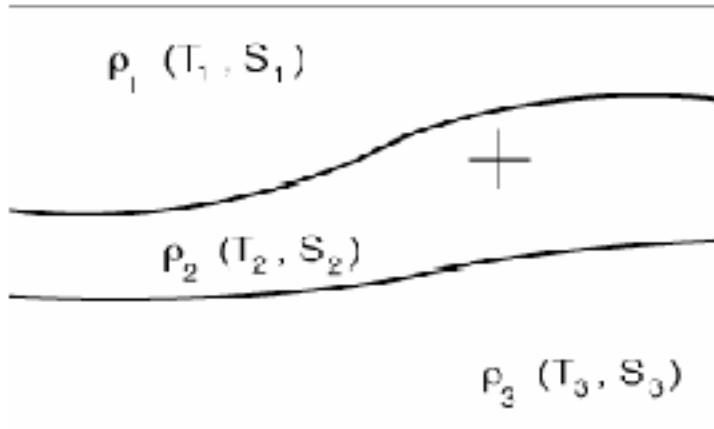


Importance of maintaining the T-S relation

1) Isopycnal nature of water movements

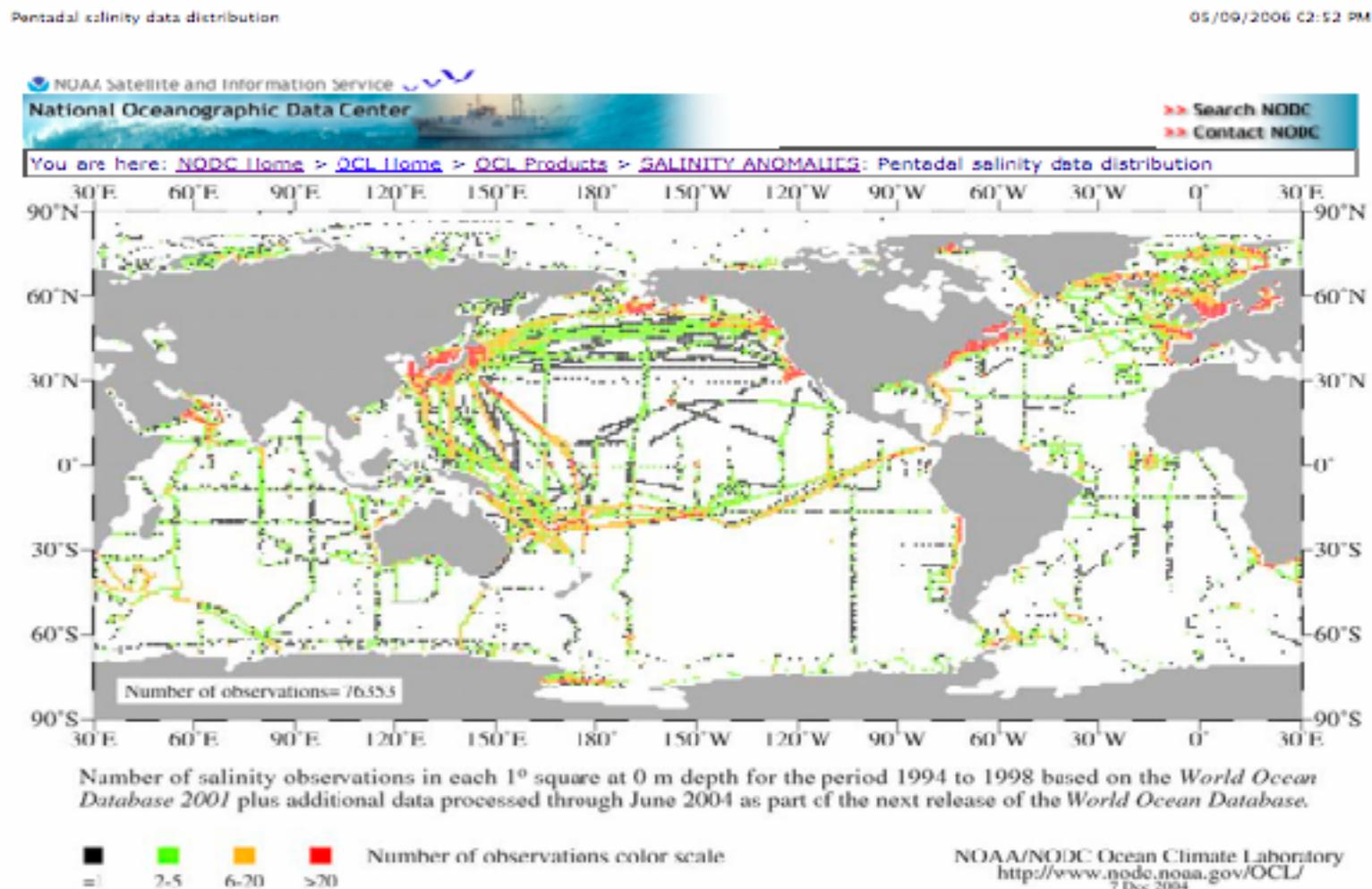
Fact: over the 20th century, salinity observations are very sparse.

We need a methodology to maintain T-S relationship where only T is observed.



Importance of maintaining the T-S relation

2) Pentadal Salinity Obs



Importance of maintaining the T-S relation

3) test cases : using 1991 month mean data

Idealized twin experiments: perfect model/observations

Assimilation Model: CM2 with GHG +NA radiative forcing

Observations: Project Jan., 1991 to Dec., 1991 CM2.0 IPCC historical run monthly mean temp/salt onto ocean XBT network, plus a white noise [$N_T(0,0.5)$ and $N_S(0,0.1)$]

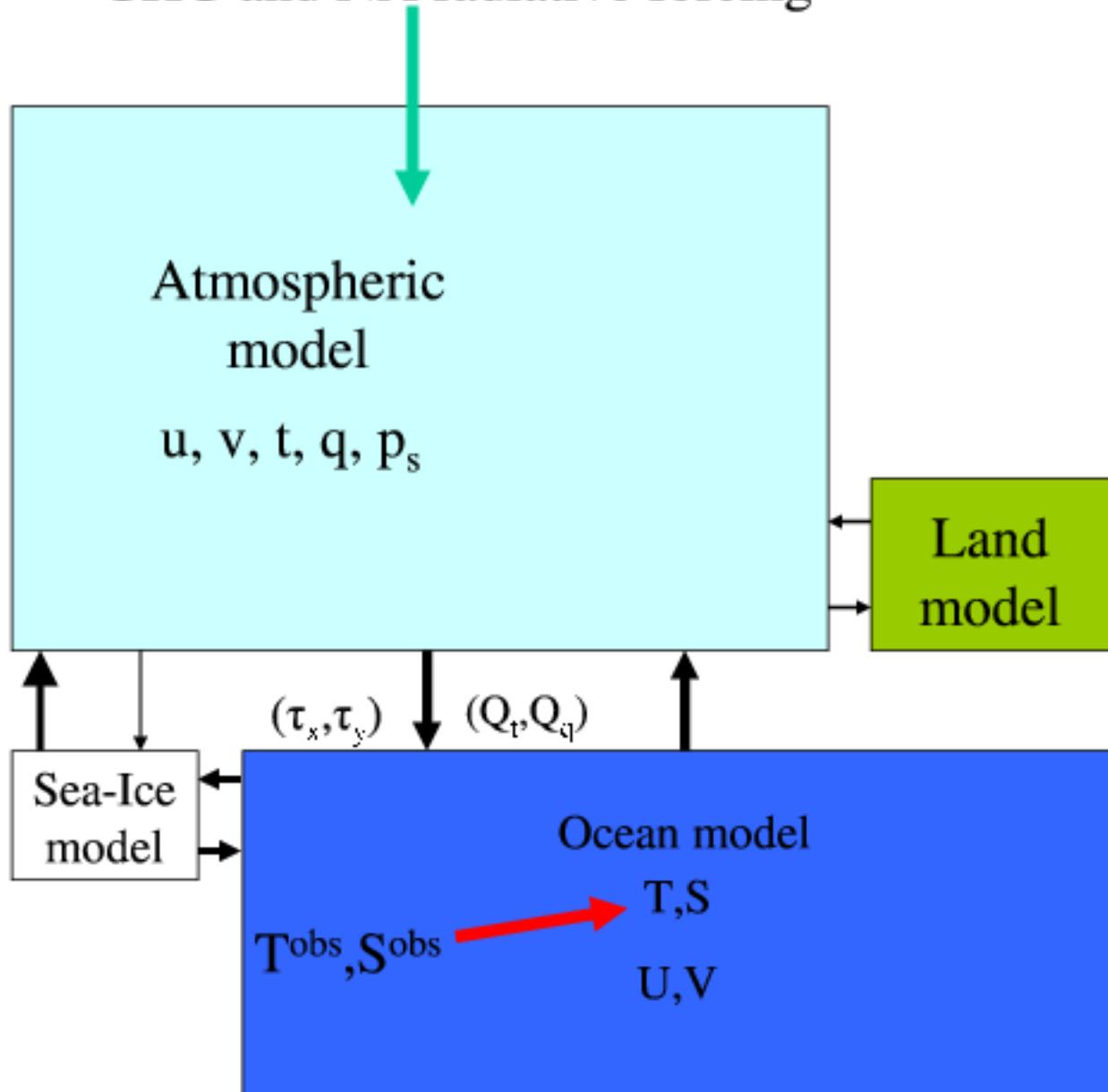
Initialize the model from arbitrary initial conditions (01/01/95)

Test cases:

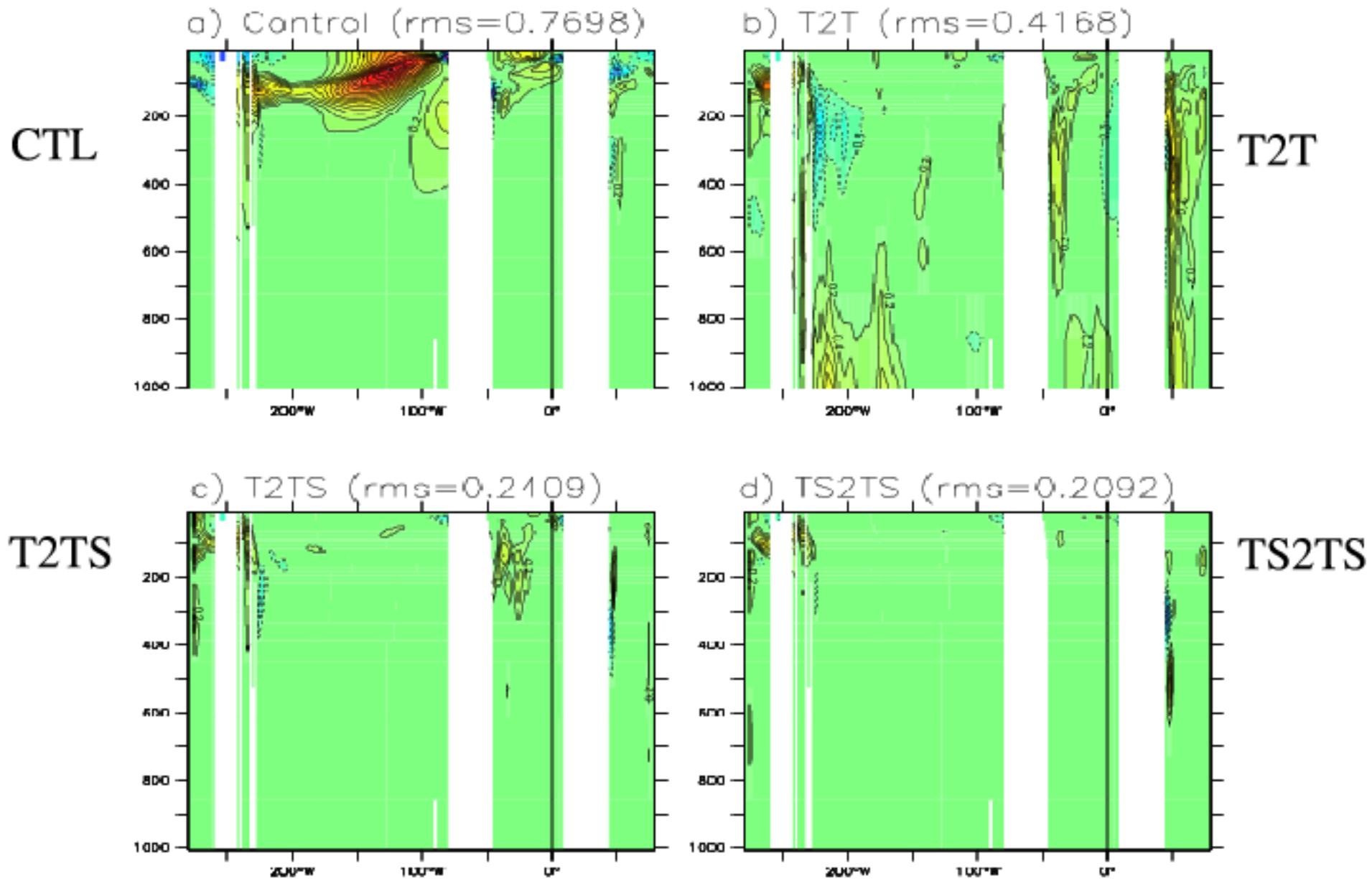
- 1) $T^{\text{obs}} \rightarrow T$ (T2T): Only allow temperature obs to correct temperature
- 2) $T^{\text{obs}} \rightarrow T, S$ (T2TS): Based on 1), using $\text{cov}(T, S)$ to correct salinity also
- 3) $T^{\text{obs}}, S^{\text{obs}} \rightarrow T, S$ (TS2TS): Using (T,S) obs and $\text{cov}(T, S)$ to correct T & S

Question: How does the filter converge to the truth?

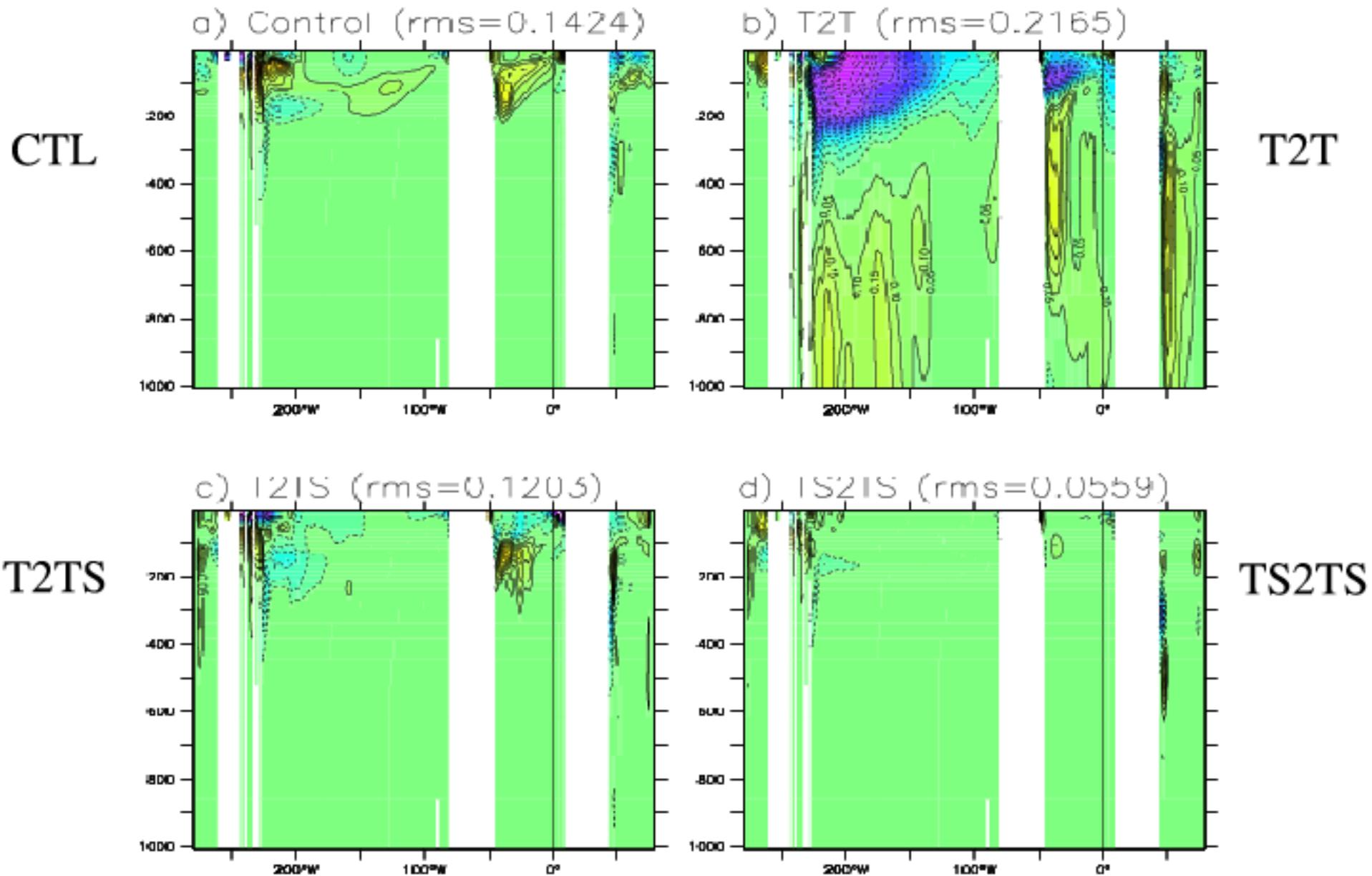
GHG and NA radiative forcing



Ocean temperature errors at equator

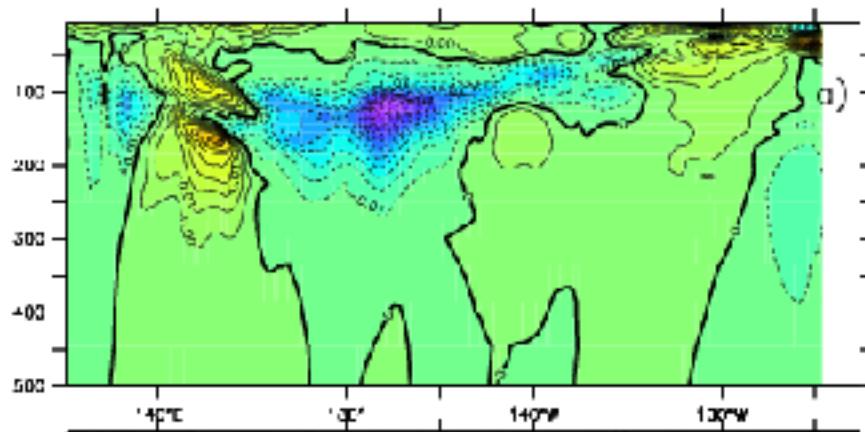


Ocean salinity errors at the equator

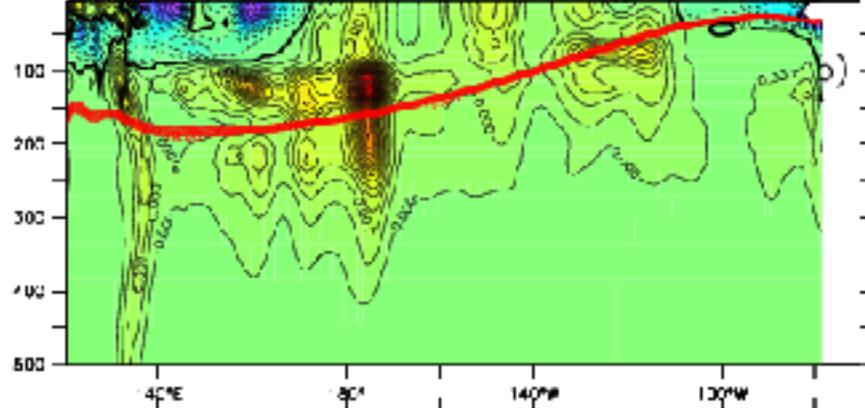


T, S corrections and T-S covariance at y=0 (1991 annual mean)

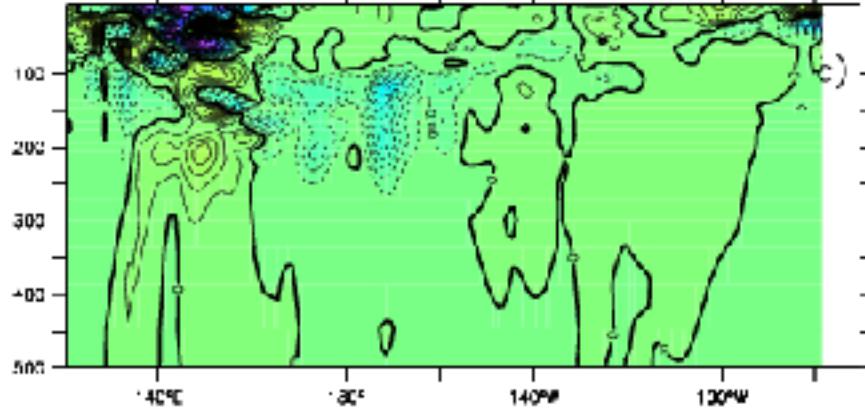
Temp correction



T-S covariance

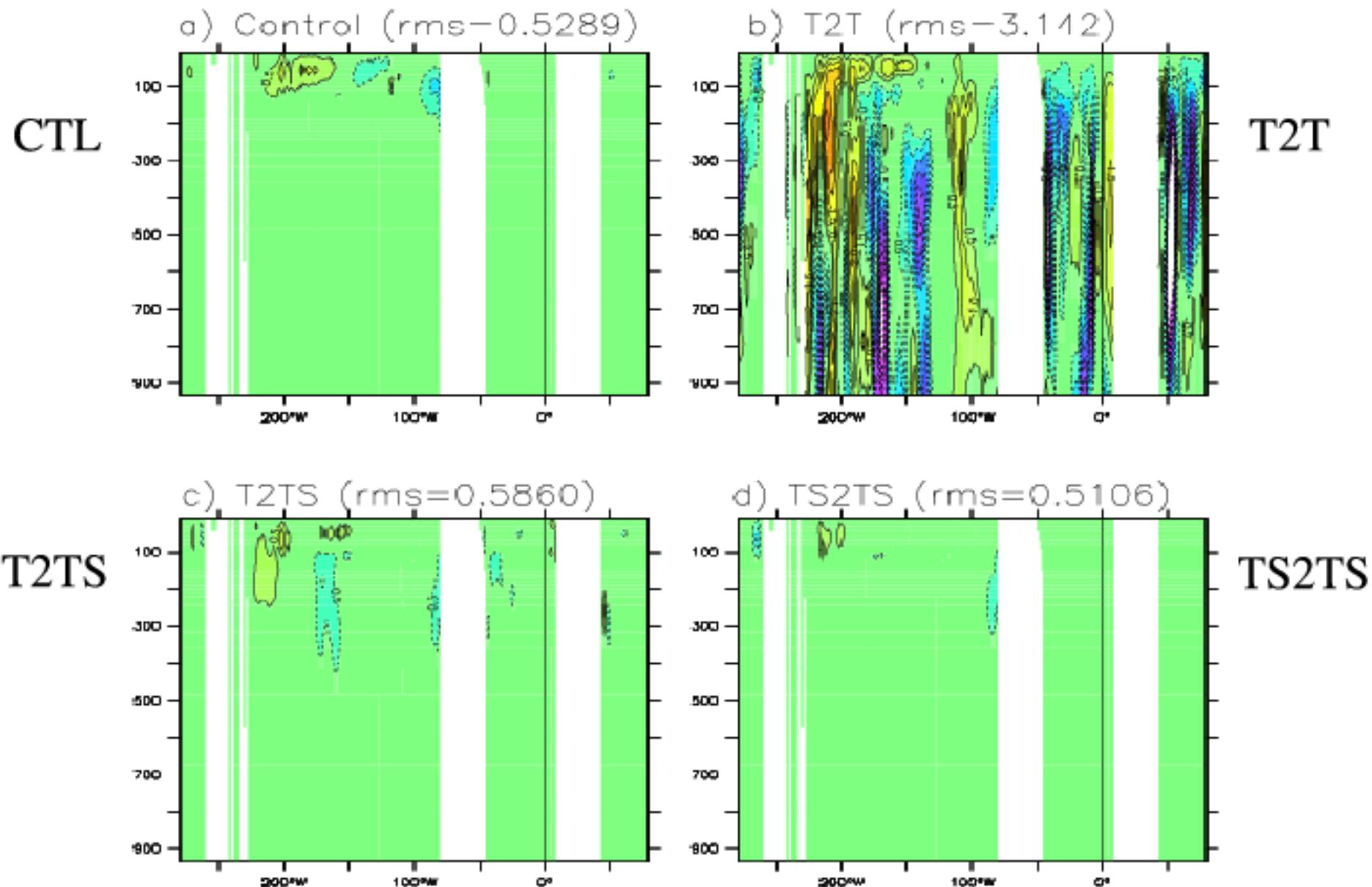


Salinity correction

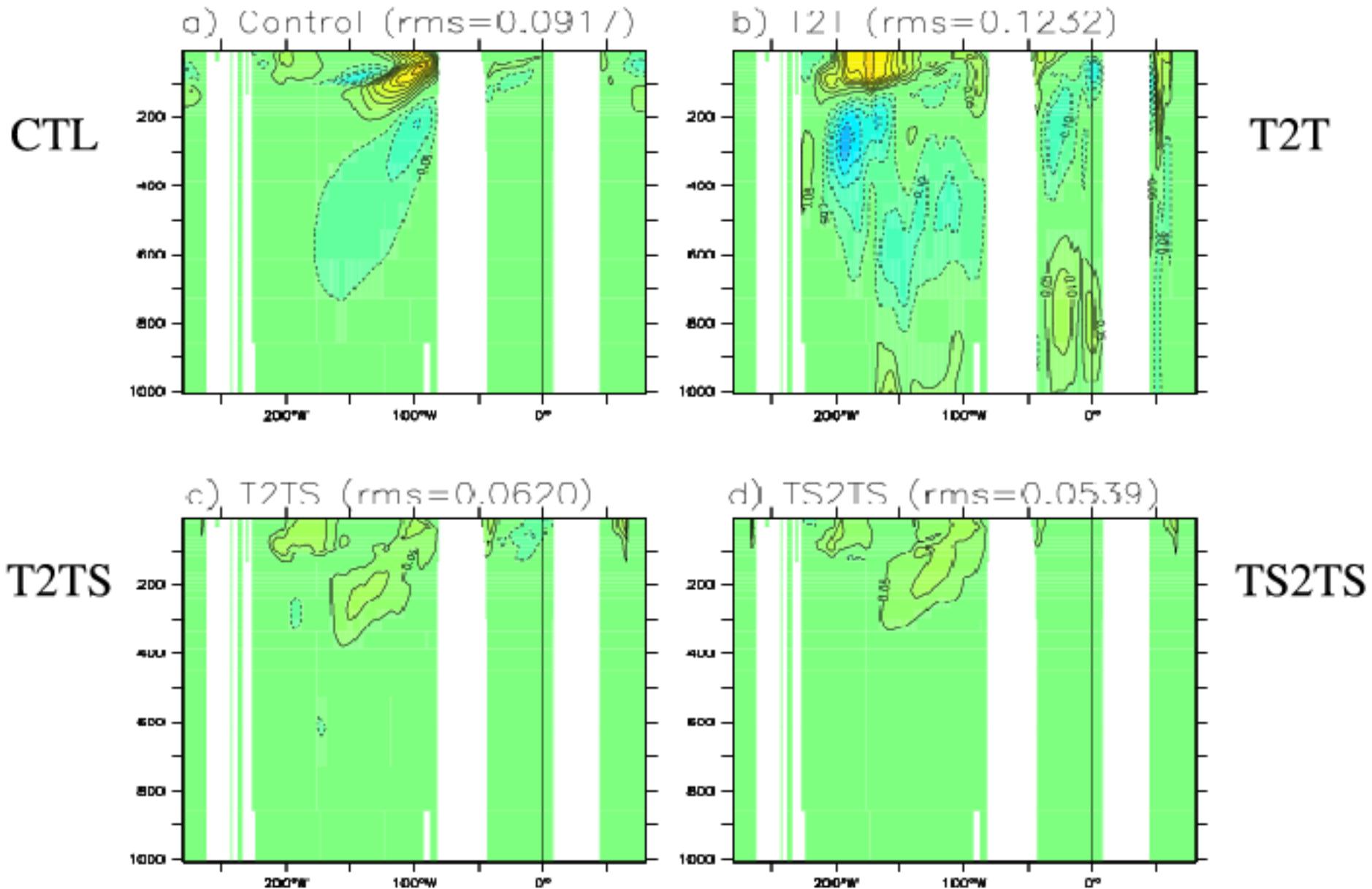


$$\Delta S = \frac{\text{cov}(T, S)}{\delta_T^2} \Delta T$$

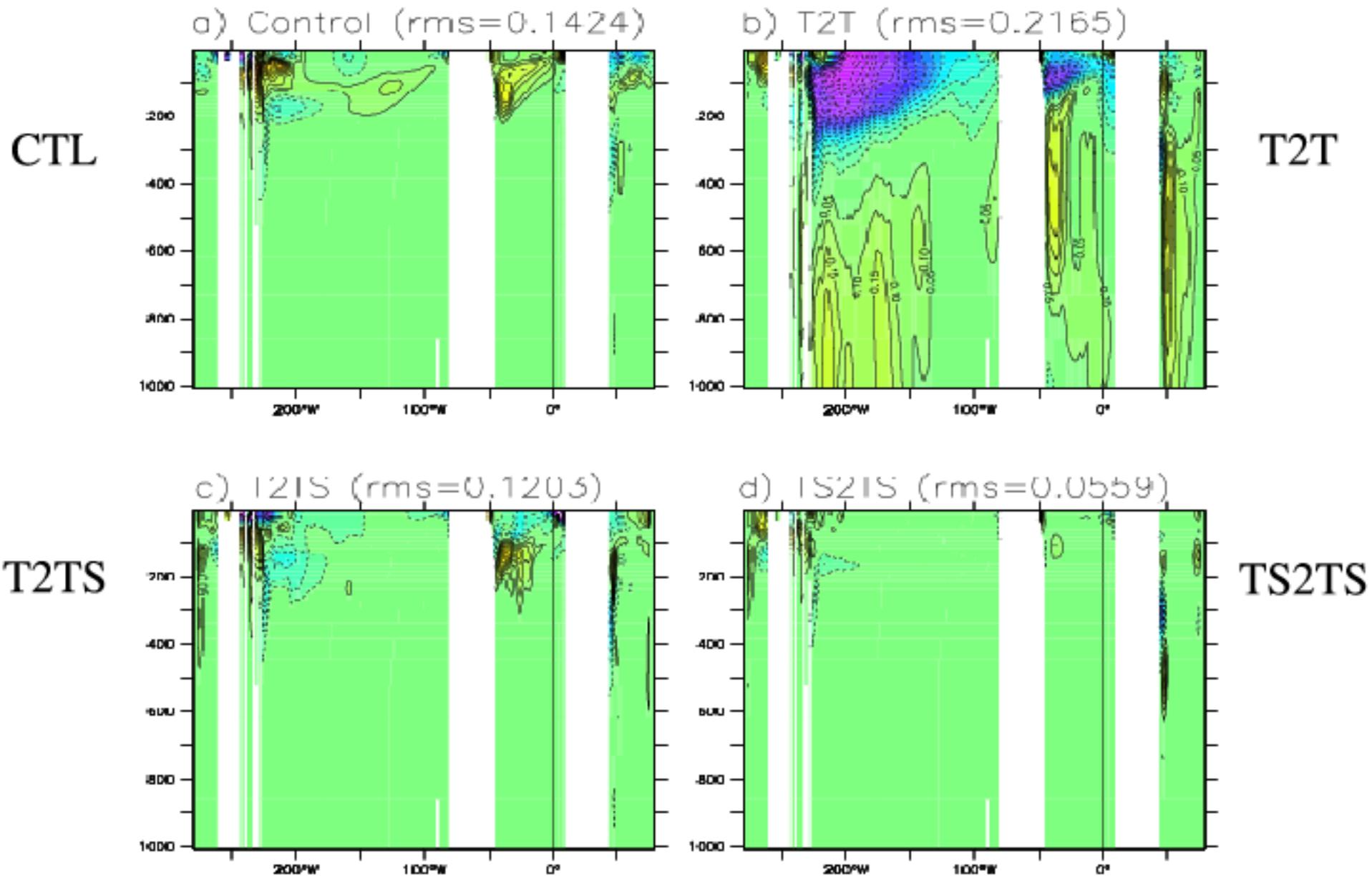
Vertical motion errors at the equator



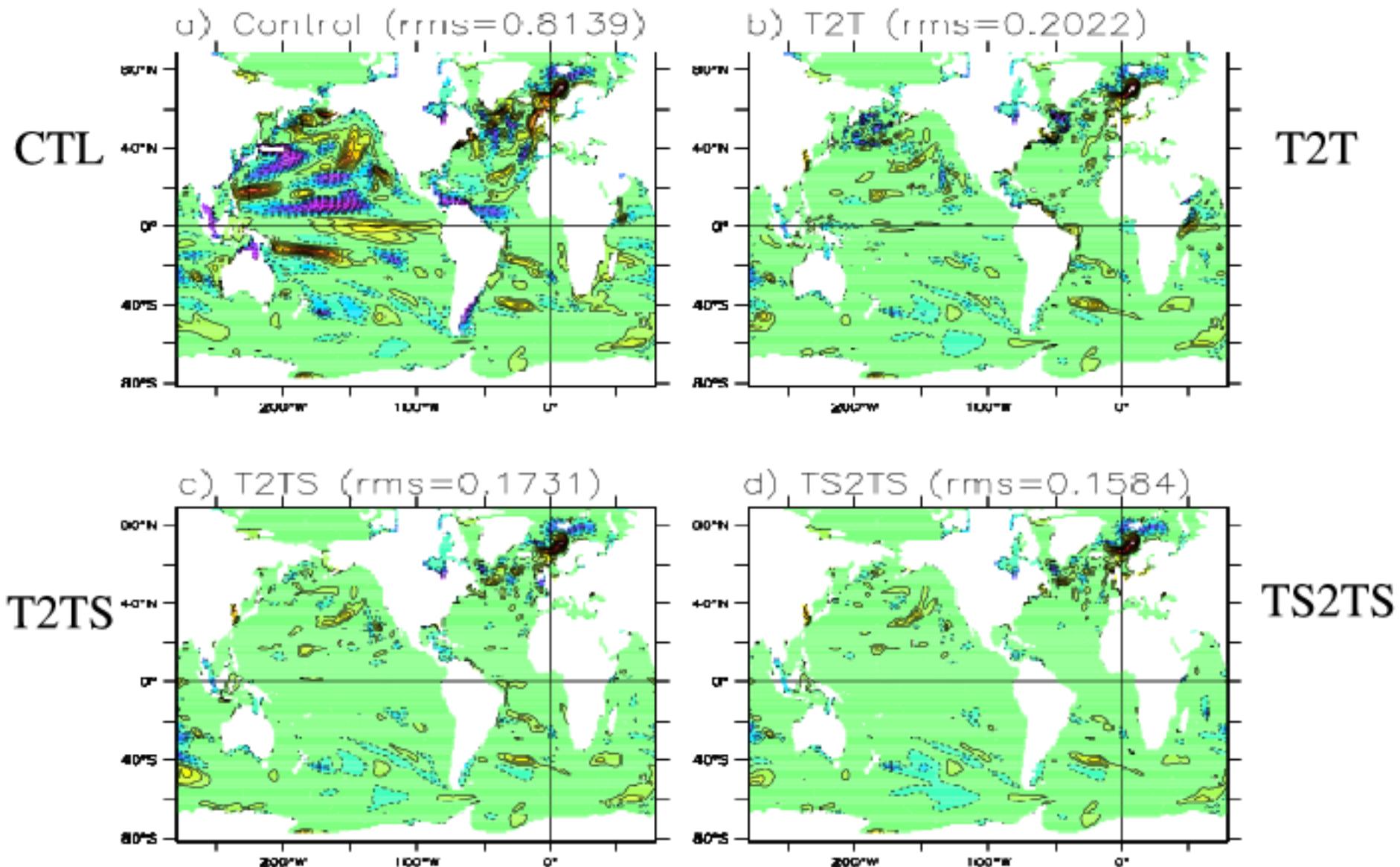
Under current errors at the equator



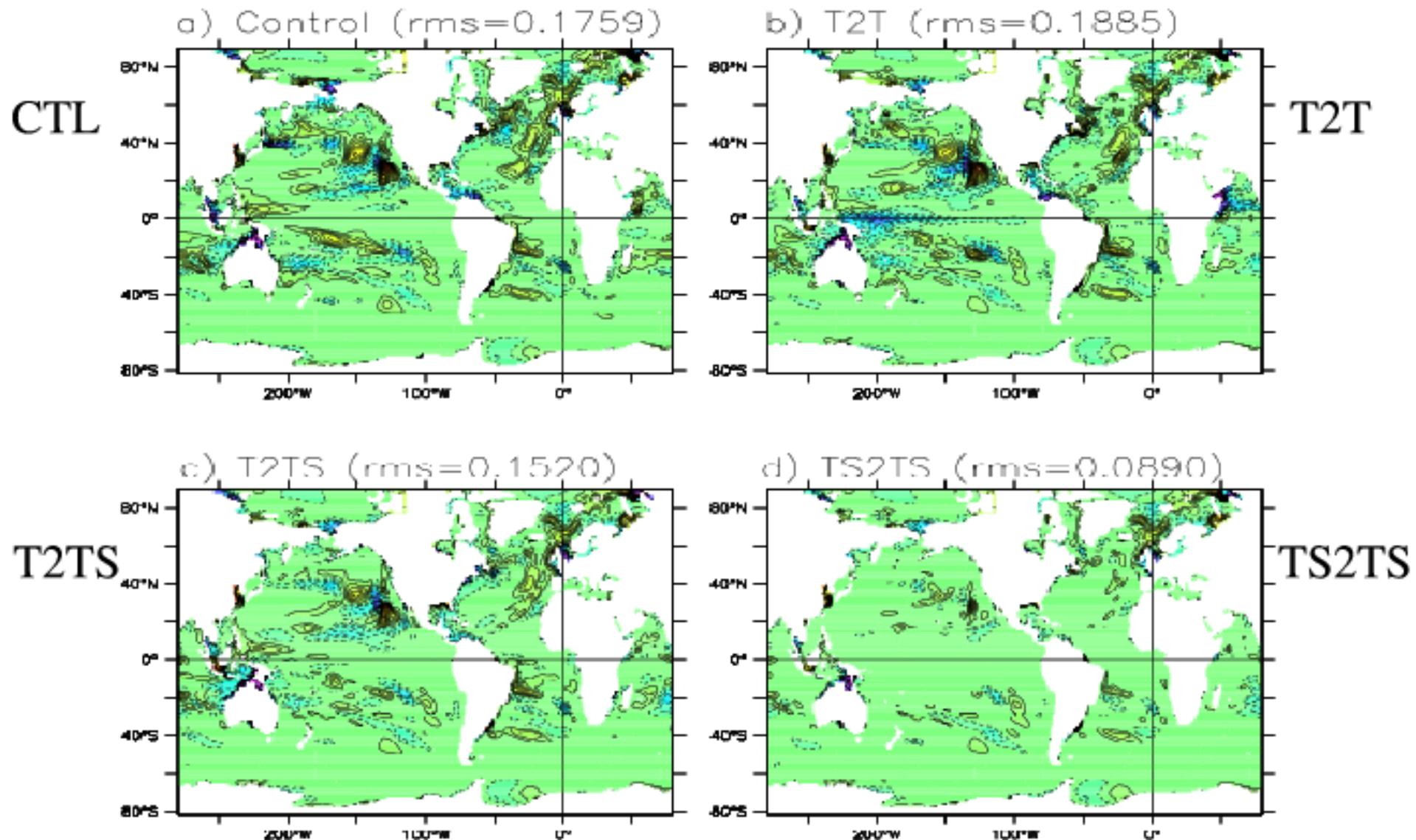
Ocean salinity errors at the equator



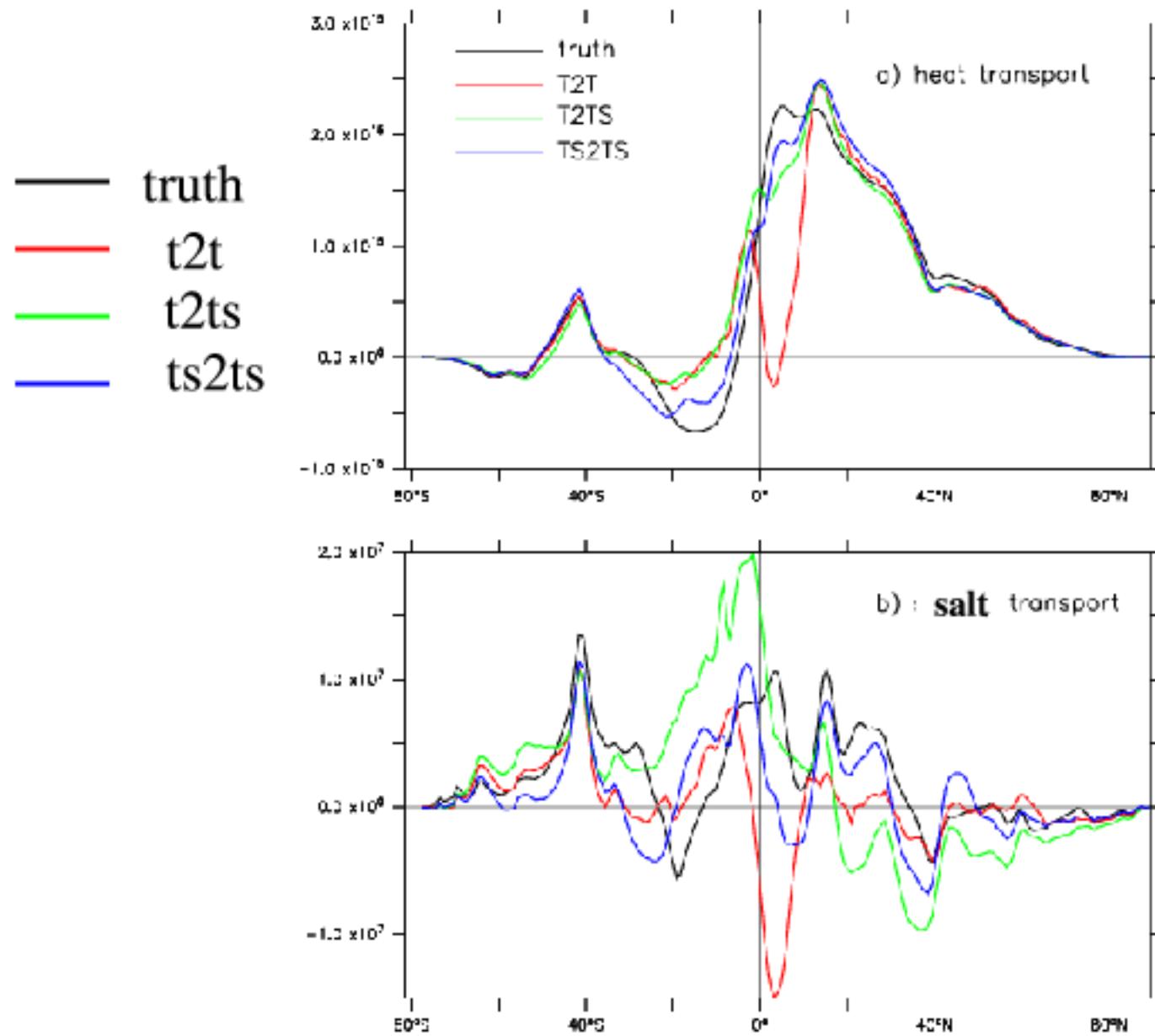
Top 500 m ocean temp error



Top 500 m ocean salinity errors



Integral of meridional heat/salinity transport in zonal-depth

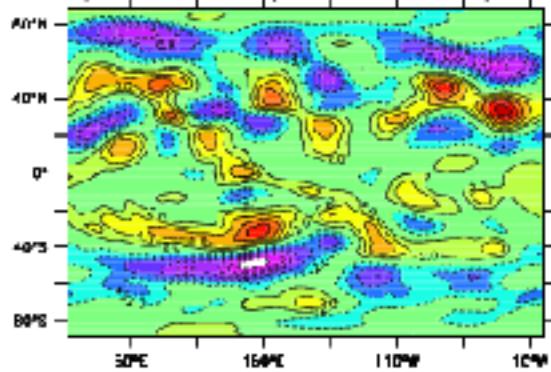


ADA Impact on Climate data assimilation: Importance of maintaining geostrophic balance

- Monthly mean atmospheric data as obs
- Daily atmospheric analysis
- Assimilate winds only
- Assimilating atmospheric temperature only
- Assimilating atmospheric winds and temperature

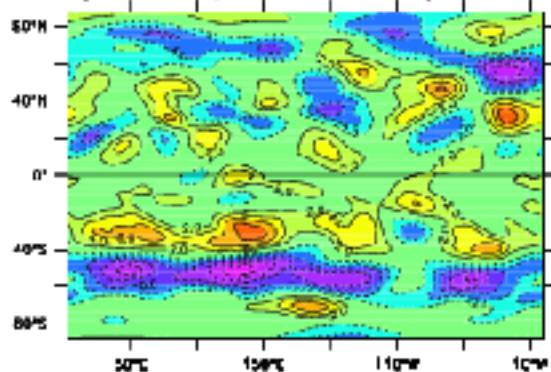
Atmospheric Zonal Wind Errors (vertical average)

a) Control (rms=5.455)



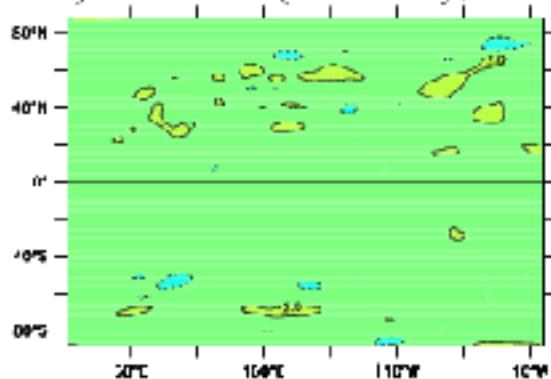
Control (without any data constraint)

b) ODA (rms=4.535)



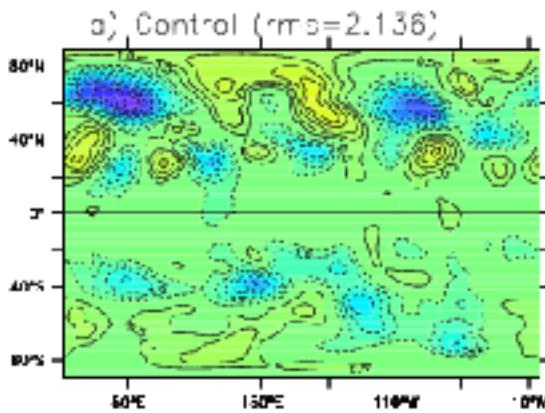
Ocean Data Assimilation (ODA) Only

c) ODA+ADA(wind only,rms=1.885)

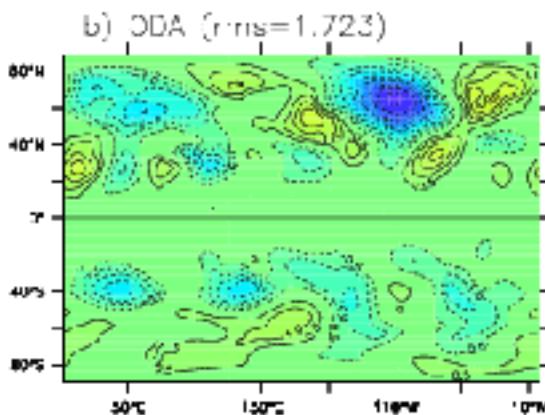


ODA and Atmosphere Data Assimilation
(ODA+ADA, wind only)

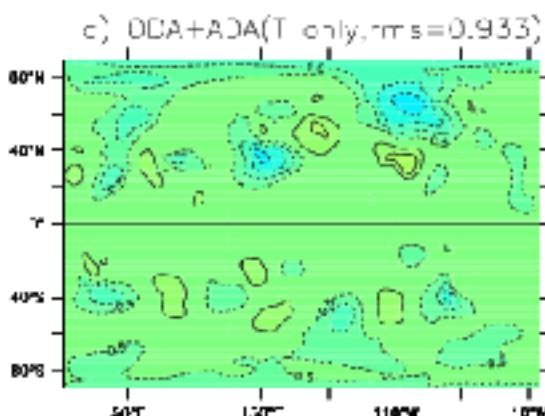
Atmospheric Temperature Errors (vertical average)



Control (without any data constraint)

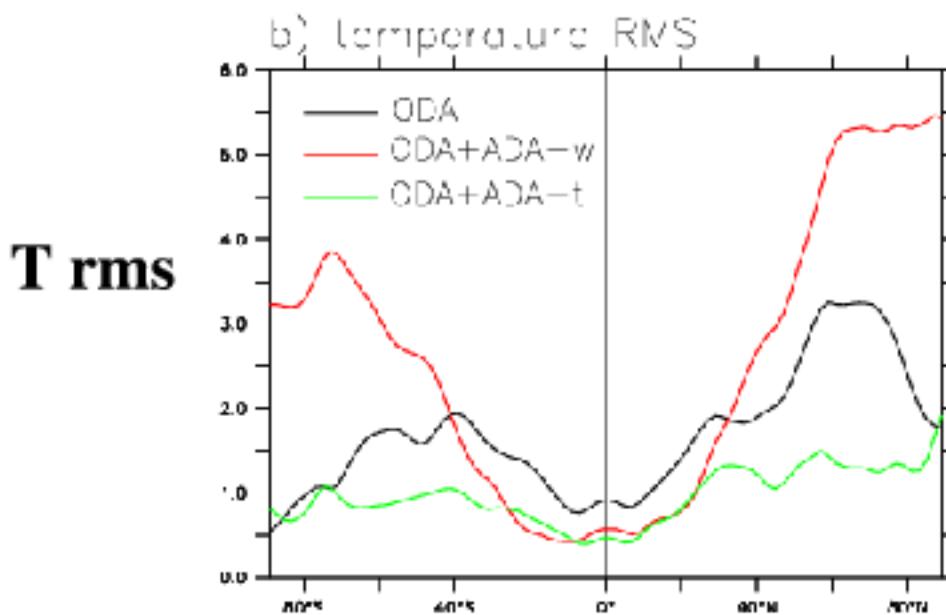
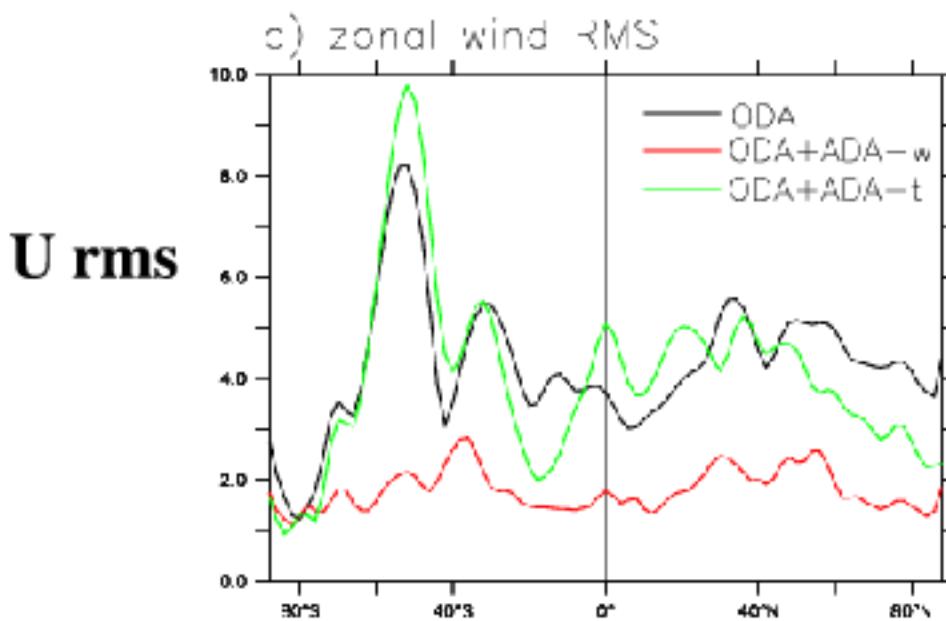


Ocean Data Assimilation (ODA) Only

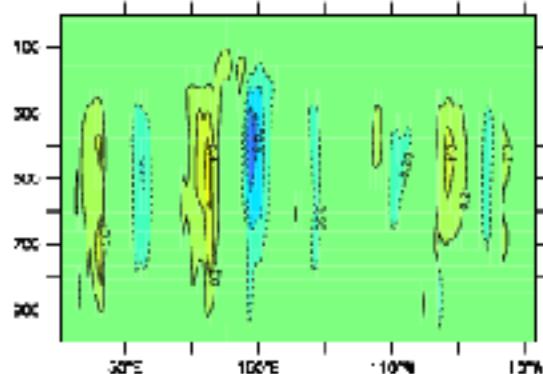


ODA and Atmosphere Data Assimilation
(ODA+ADA, T only)

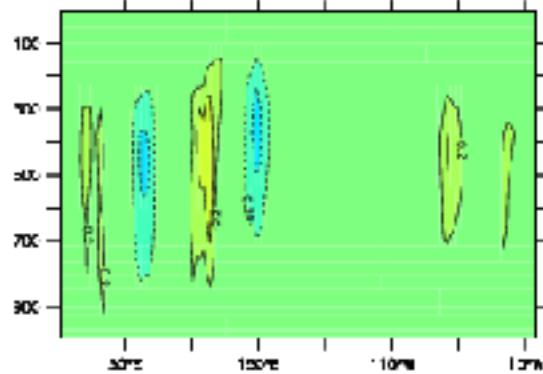
Atmospheric U & T rms errors



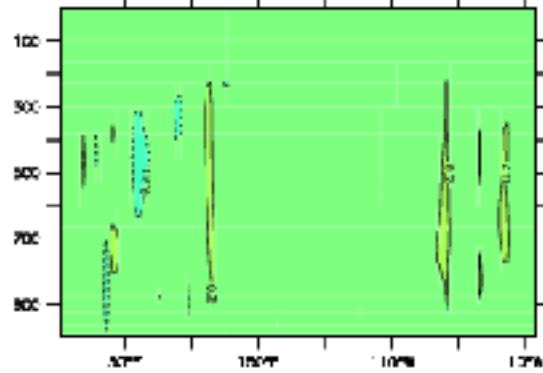
Atmosphere Vertical Motion (Walker Cell) Errors at Tropics (20°S – 20°N average)



Control (without any data constraint)

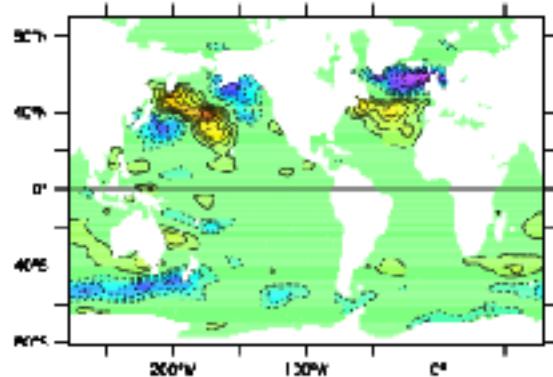


Ocean Data Assimilation (ODA) Only

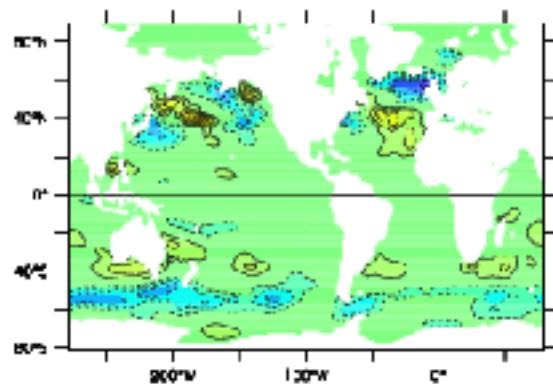


Ocean and Atmosphere Data Assimilation
(ODA+ADA)

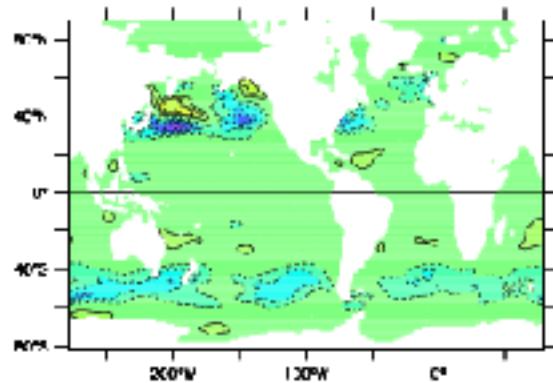
Zonal Wind Stress Errors at Ocean Surface Exerted by The Atmosphere Bottom



Control (without any data constraint)



Ocean Data Assimilation (ODA) Only



Ocean and Atmosphere Data Assimilation
(ODA+ADA)

Climate change detection for the last quarter of 20th century?

Idealized twin experiments:

- § Truth: 20th Century climate simulation forced by time-varying green-house-gas radiation (IPCC historical run)
- § Observations: Projecting the IPCC historical run temperature onto 20th century ocean temperature observational network (XBT, CDT, MBT, OSD, ...), plus an $N(0,0.5)$ white noise

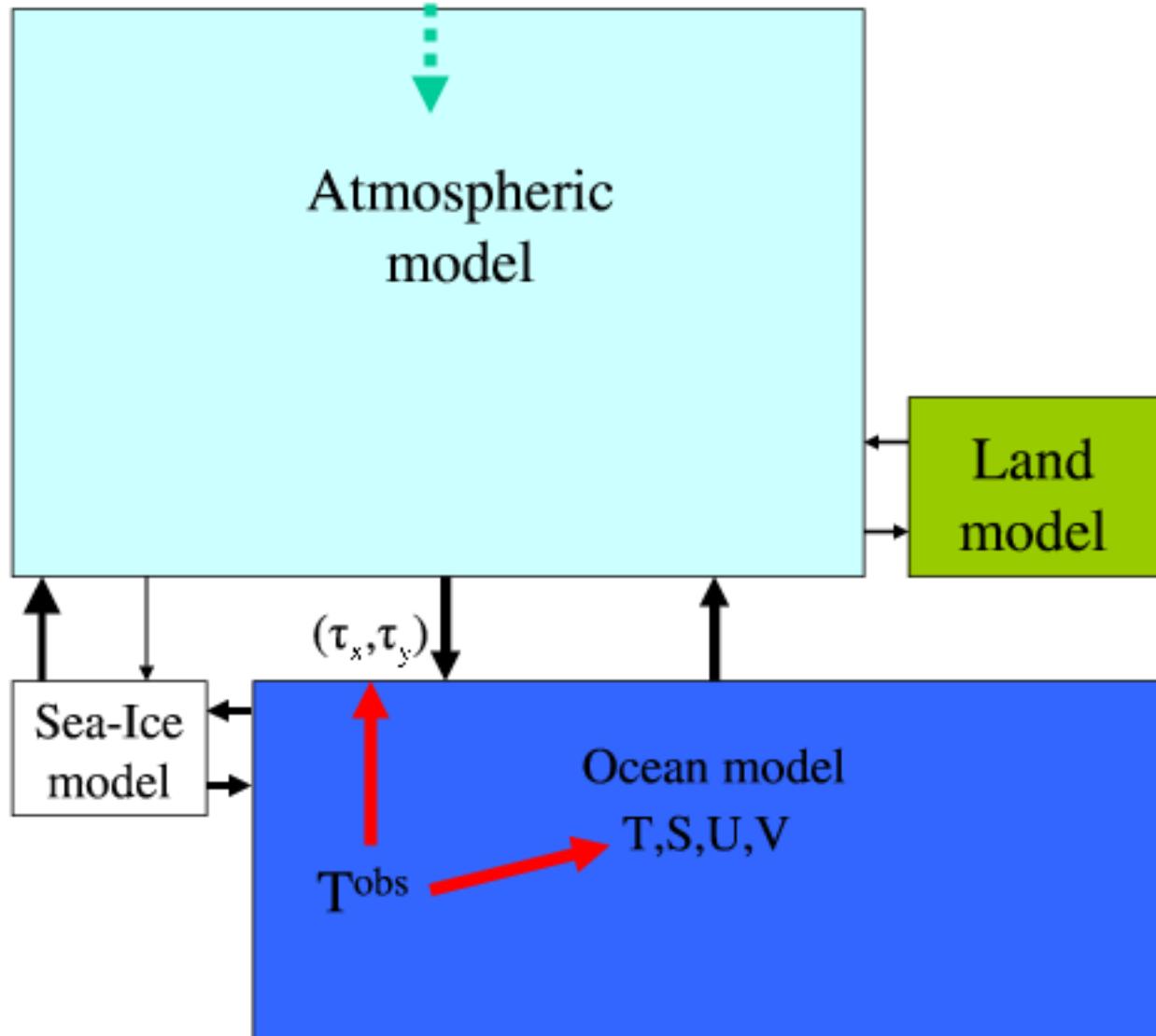
Assimilation Model: CM2 control run -- **without time varying GHGNA forcing**

- § B-grid atmospheric model, 144x90x24 and Land model (LM2.0)
- § Version 4 of module ocean model (MOM4), 360x200x50 and Sea Ice Simulator (SIS)

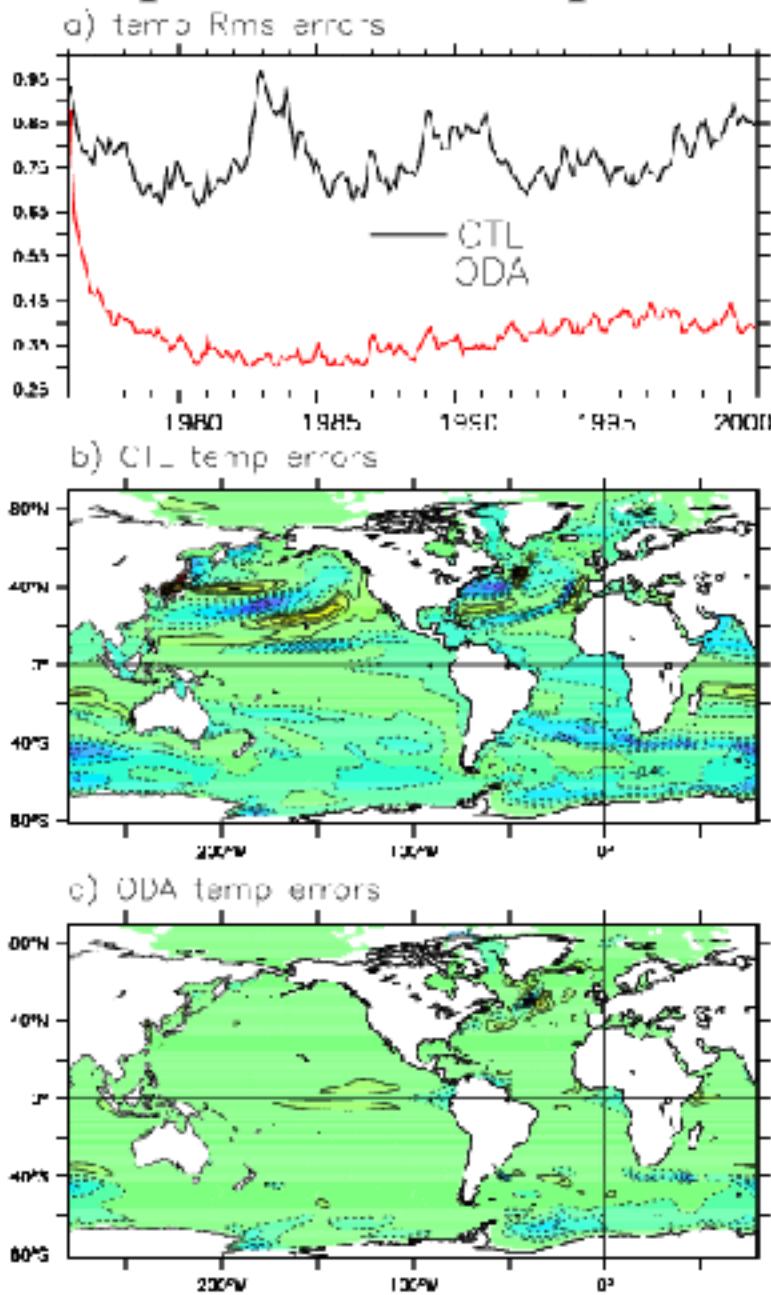
Initialize the model from arbitrary initial conditions (75 years ago, for instance)

Question: How much can we retrieve signals of climate change, both variability and trend, given the 20th century temperature observational network?

1860 GHG and NA radiative forcing



Temp errors over top 500m



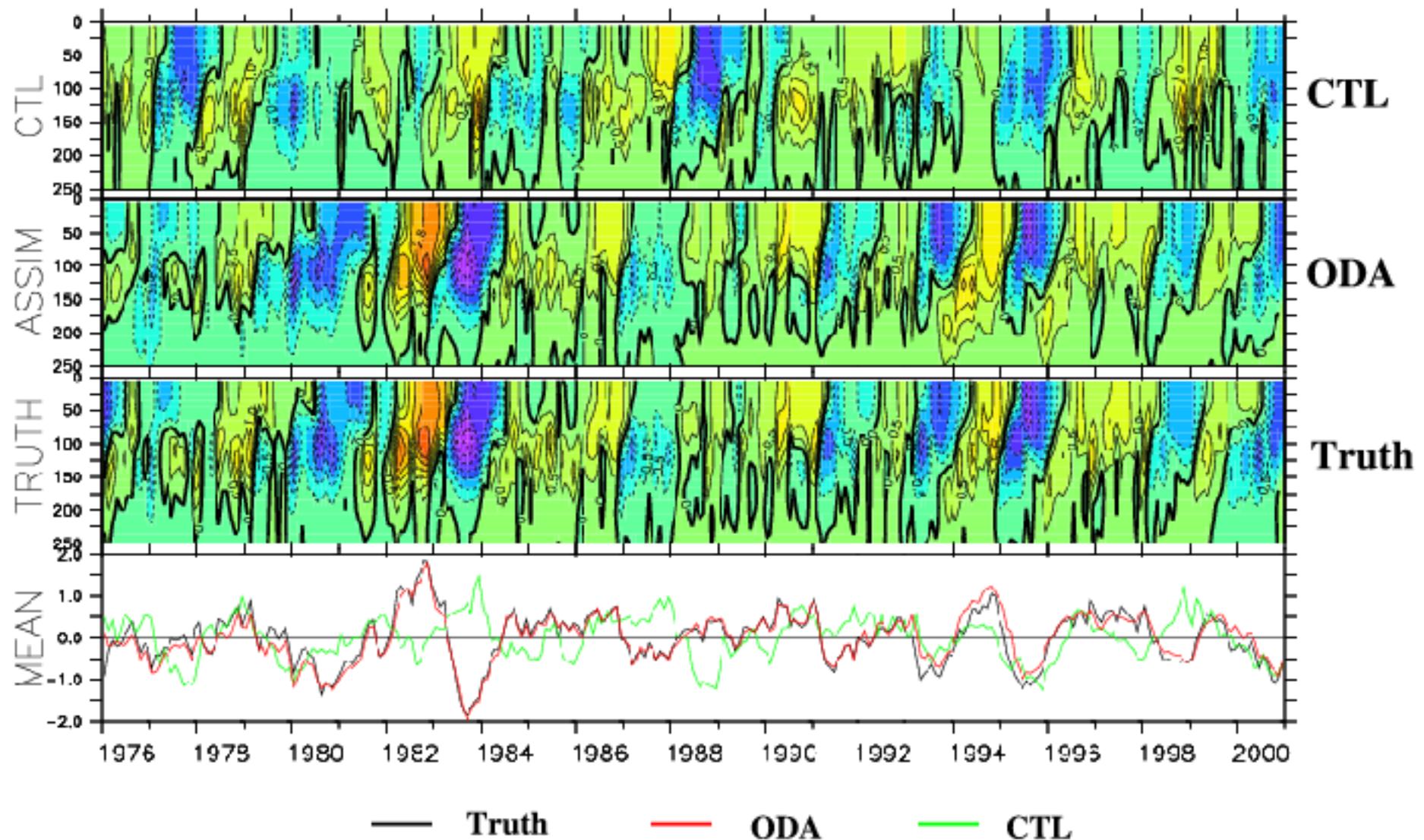
Global Rms error

CTL Averaged errors

ODA Averaged errors

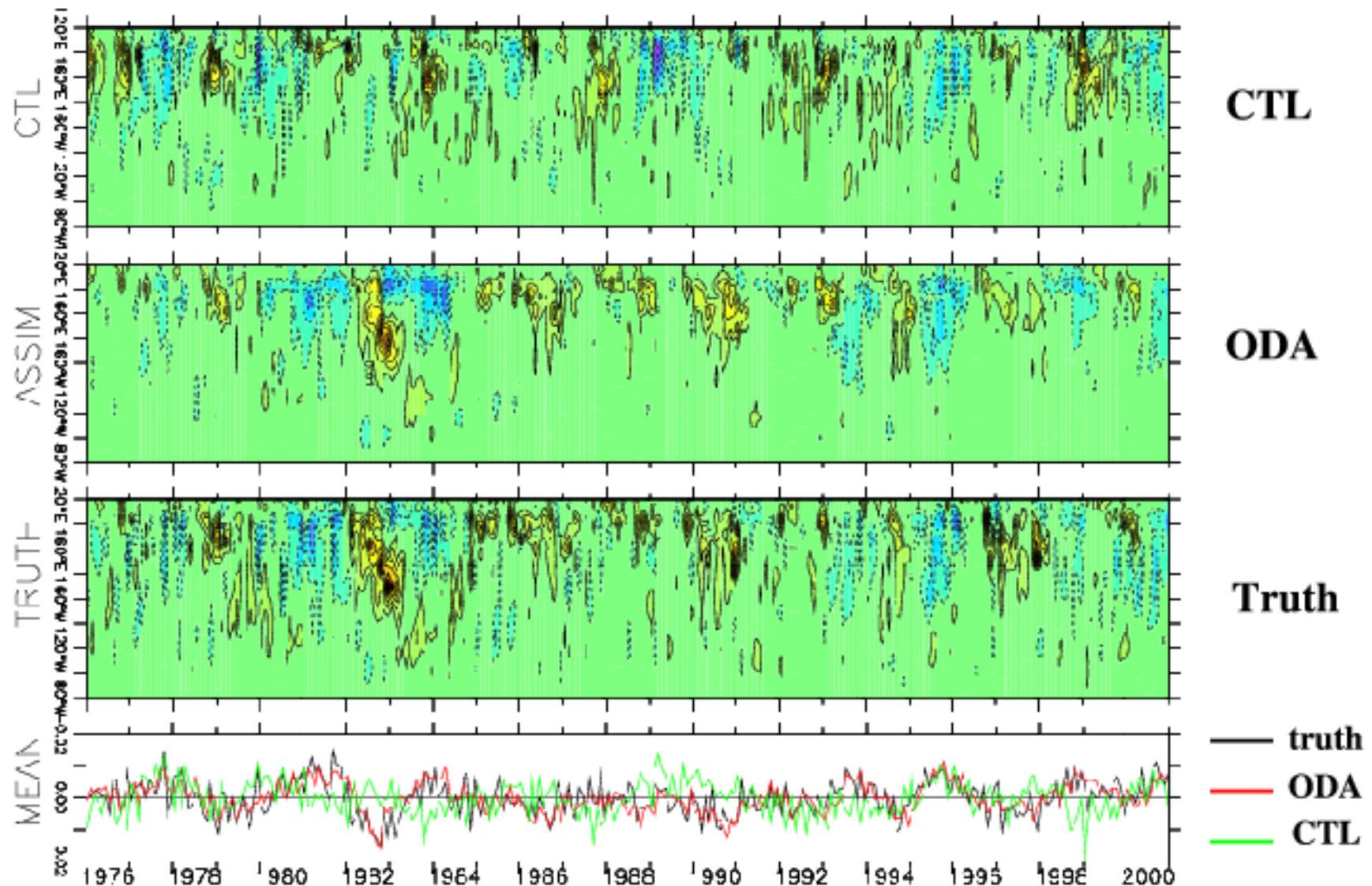
25yr climate detection: ENSO variability

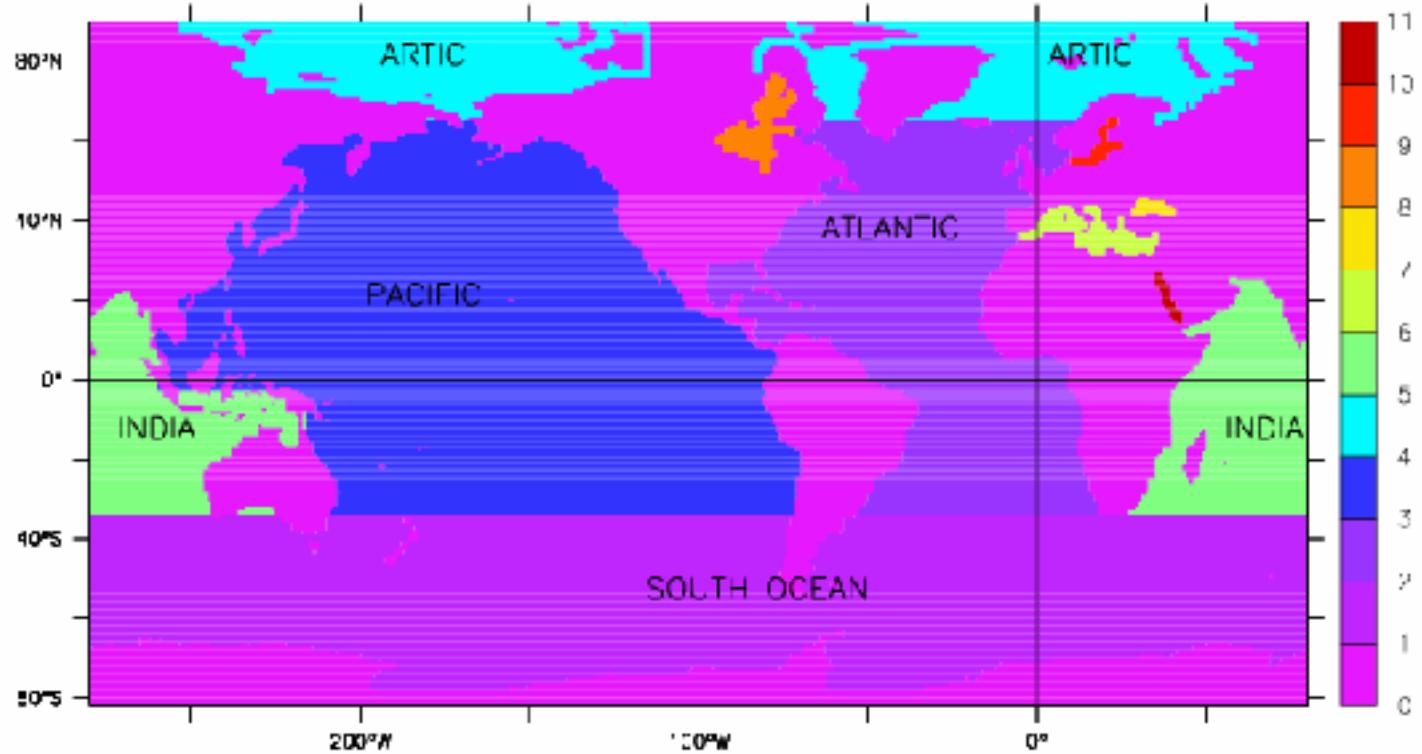
1) Temperature at NINO3.4



25yr climate detection: ENSO variability

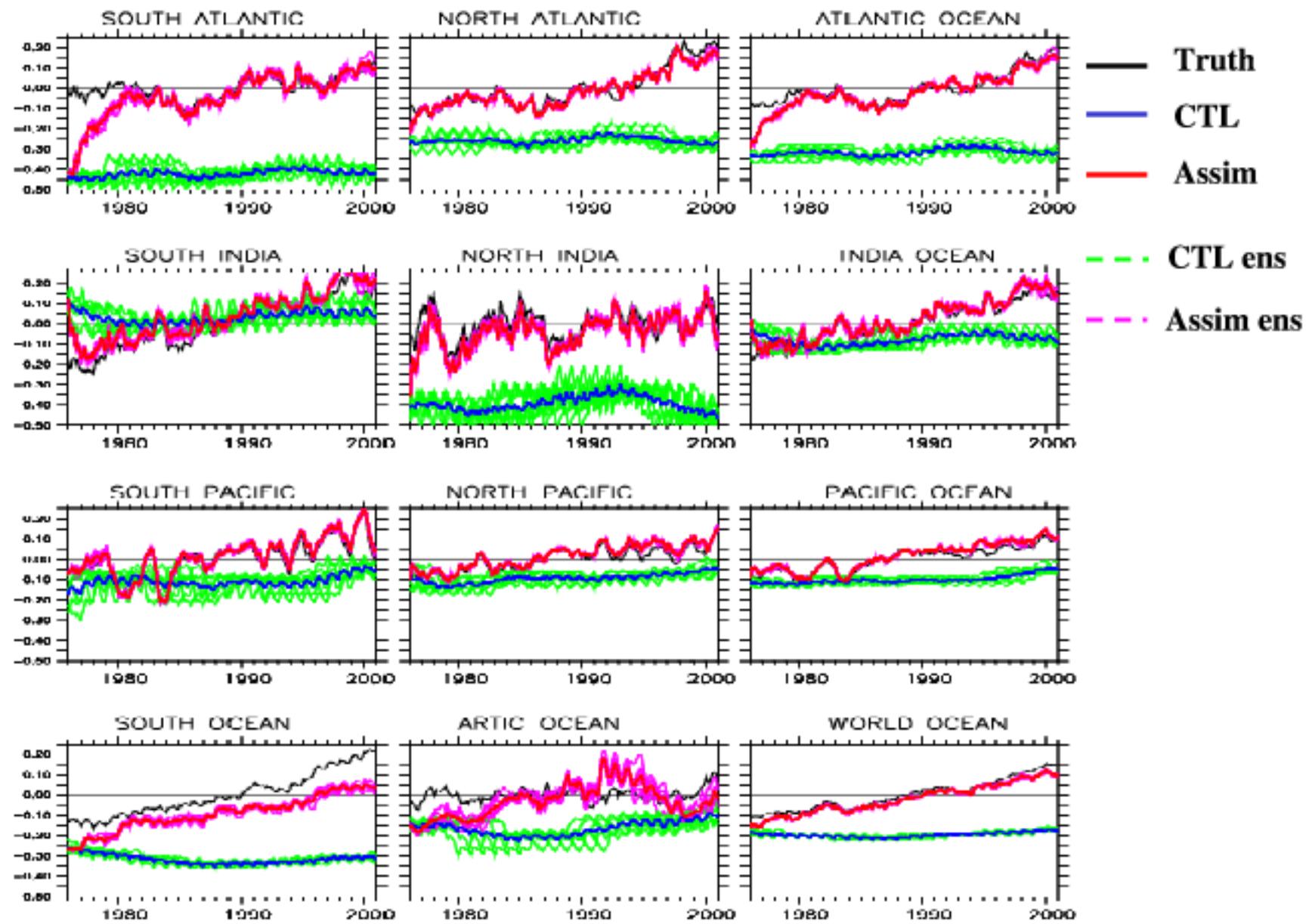
2) Zonal wind stress (τ_x) at tropical Pacific (5S-5N average)





How much can we retrieve the trend of climate change?

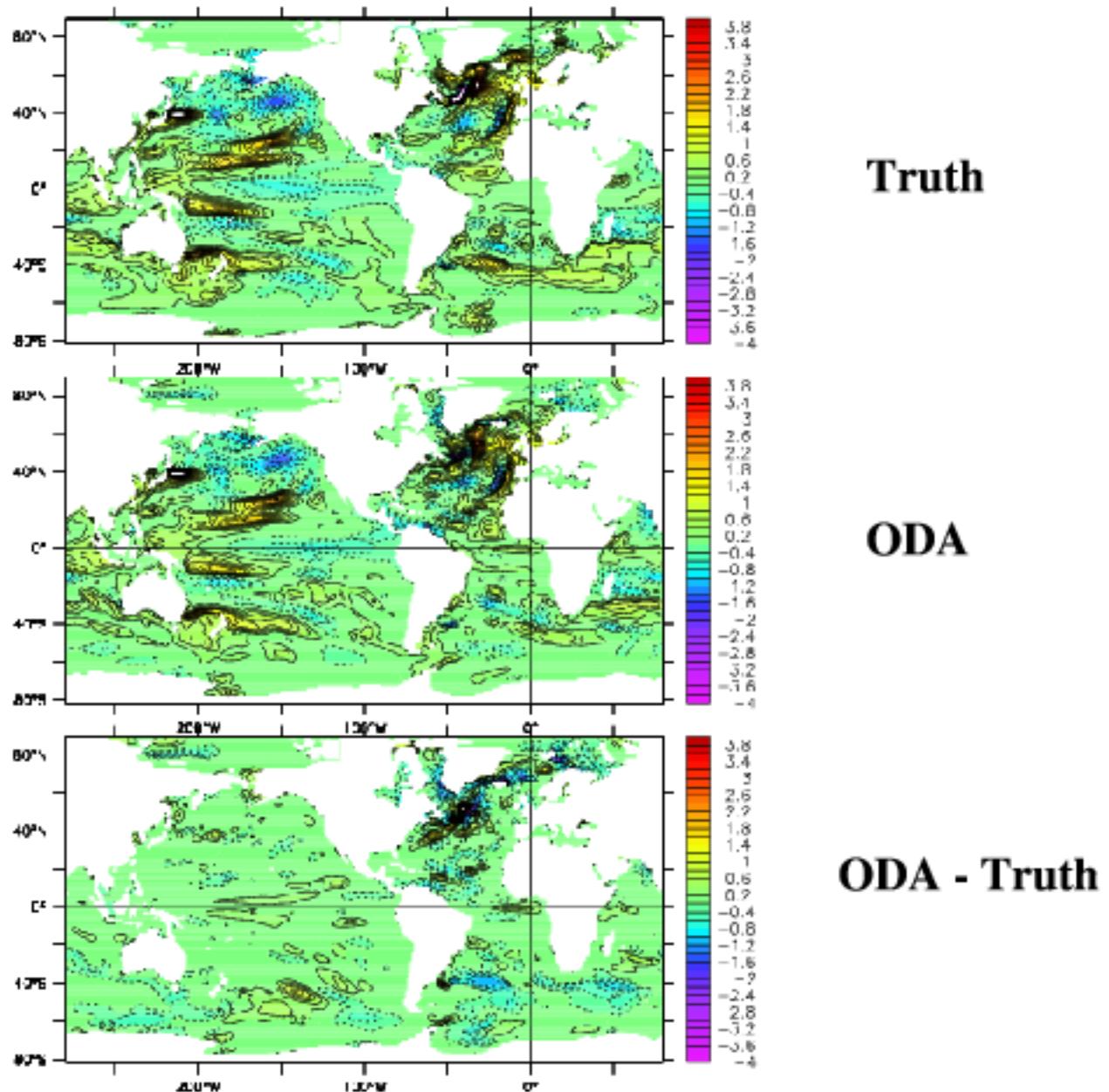
1) Top 500 m Ocean Heat Content (Averaged Temperature) Anomalies



How much can we retrieve the trend of climate change?

2) Top 500 m
ocean heat content
10yr tendency
(2000 – 1990)

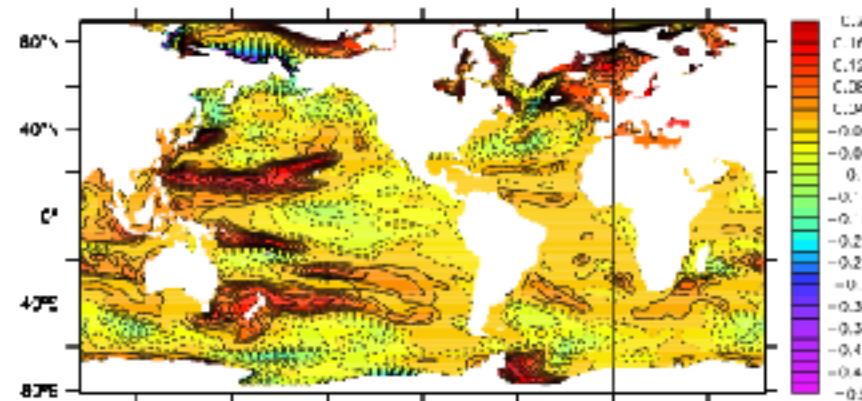
Contour interval
= 0.2 °C



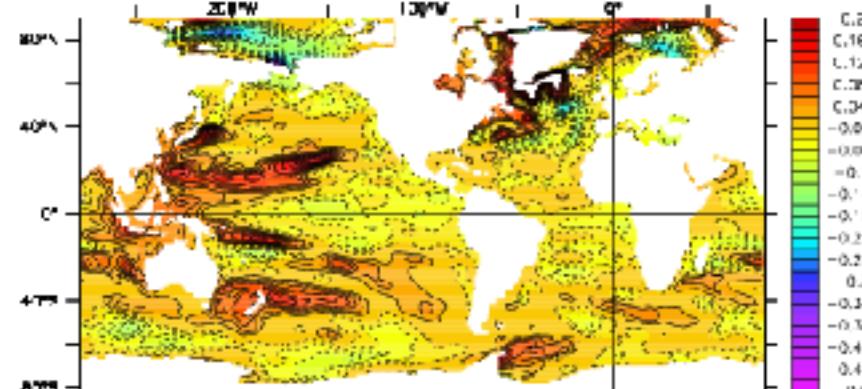
How much can we retrieve the trend of climate change?

3) Sea surface height 10yr tendency (2000 – 1990)

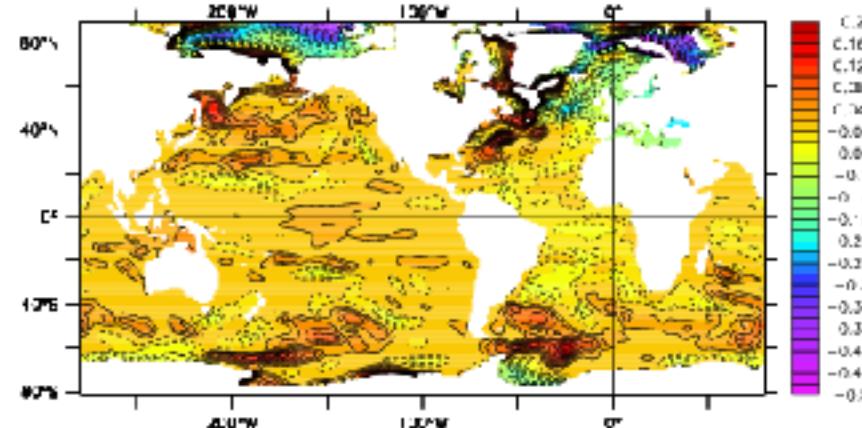
Contour interval
= 0.02 (m)



Truth



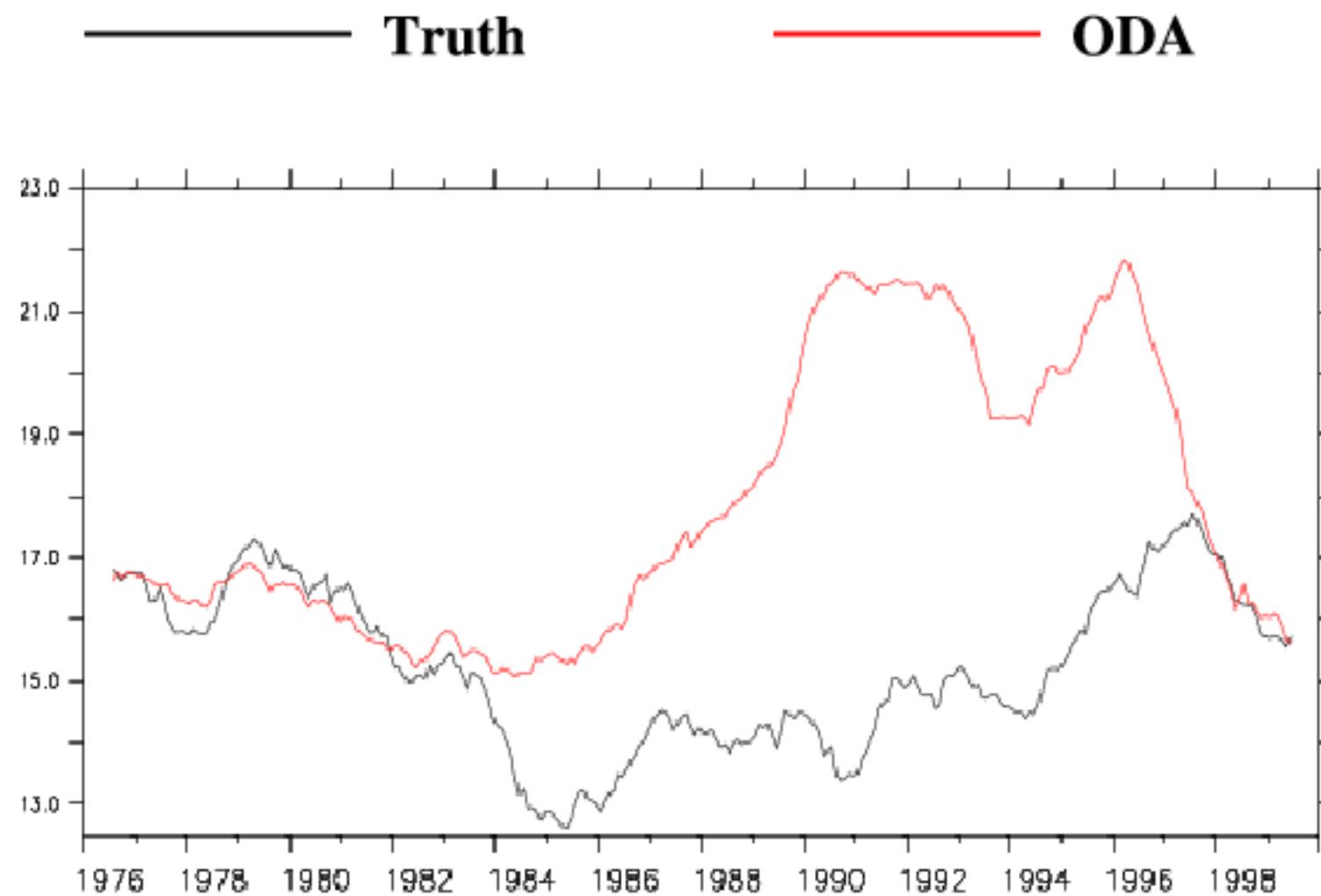
ODA



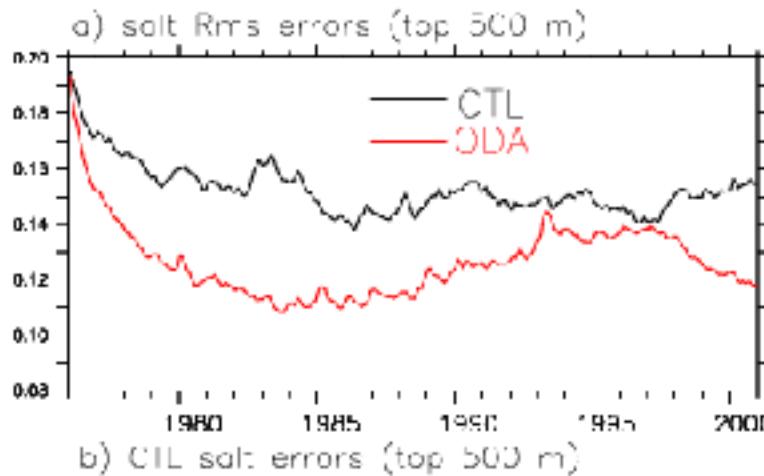
ODA - Truth

Challenges:

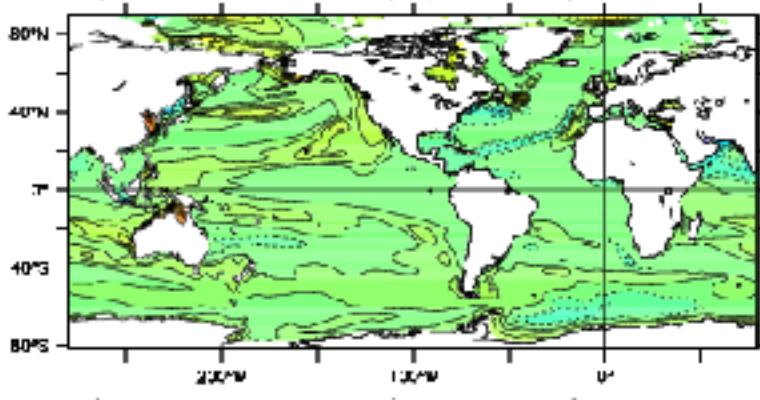
I. North Atlantic Meridional Overturning



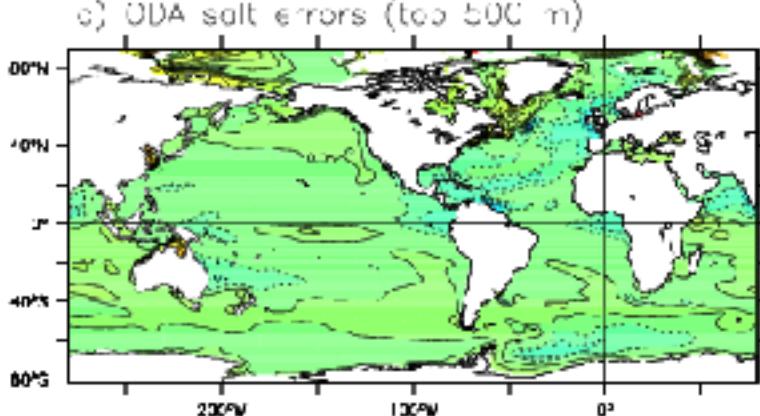
2) Salinity errors over top 500m



Global Rms error

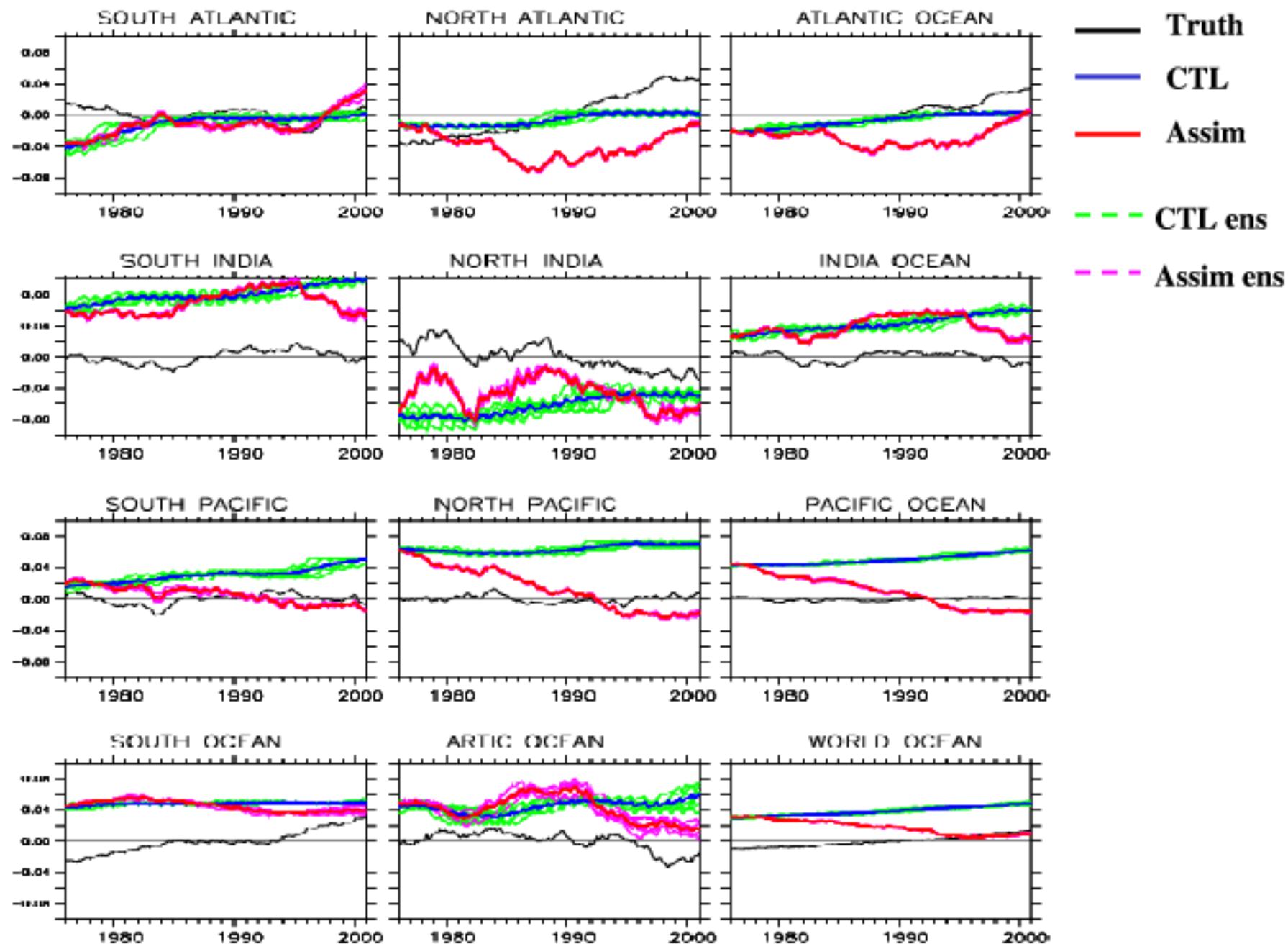


CTL Averaged errors



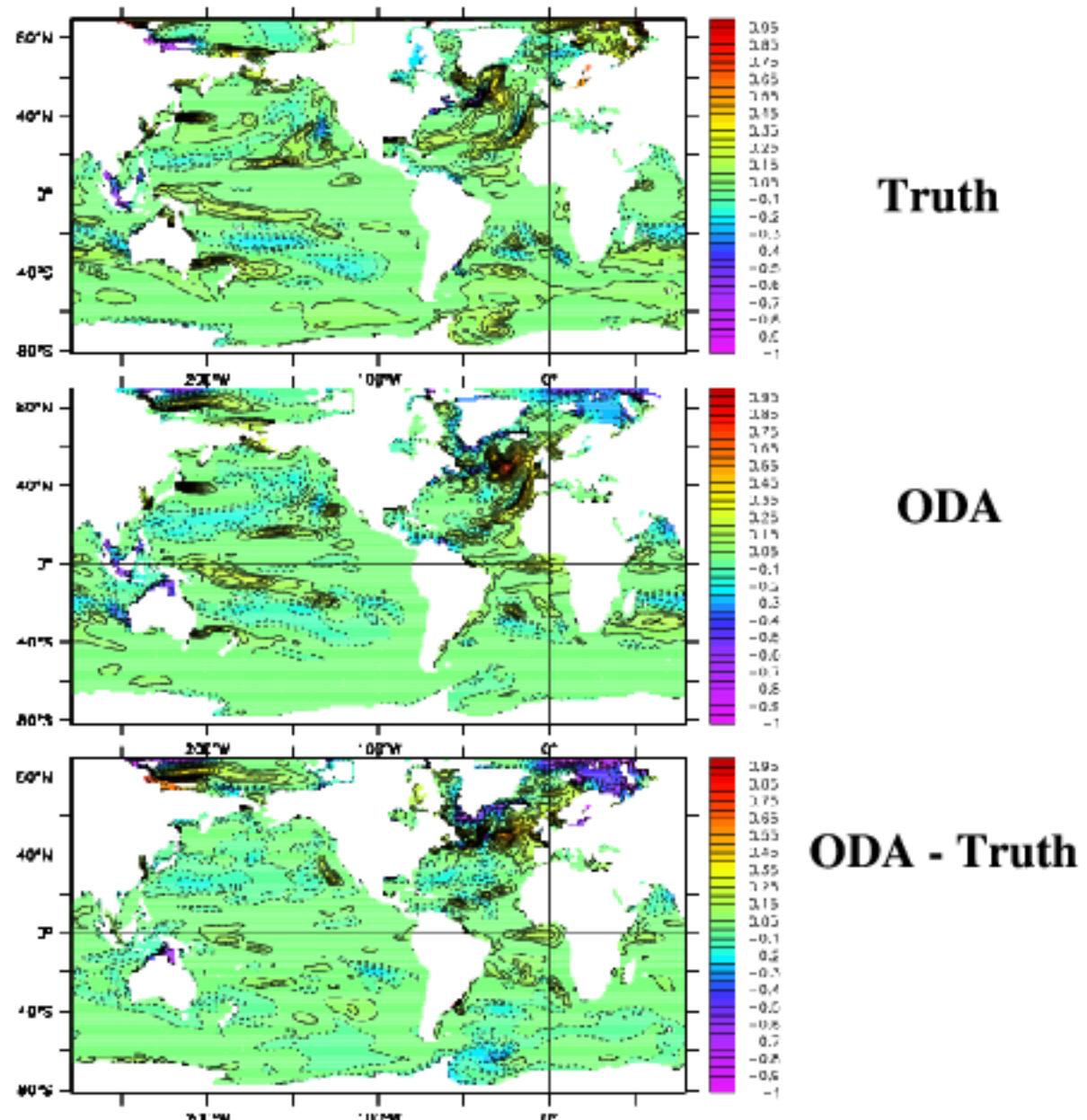
ODA Averaged errors

Challenge: 2) Top 500 m Salt Anomalies

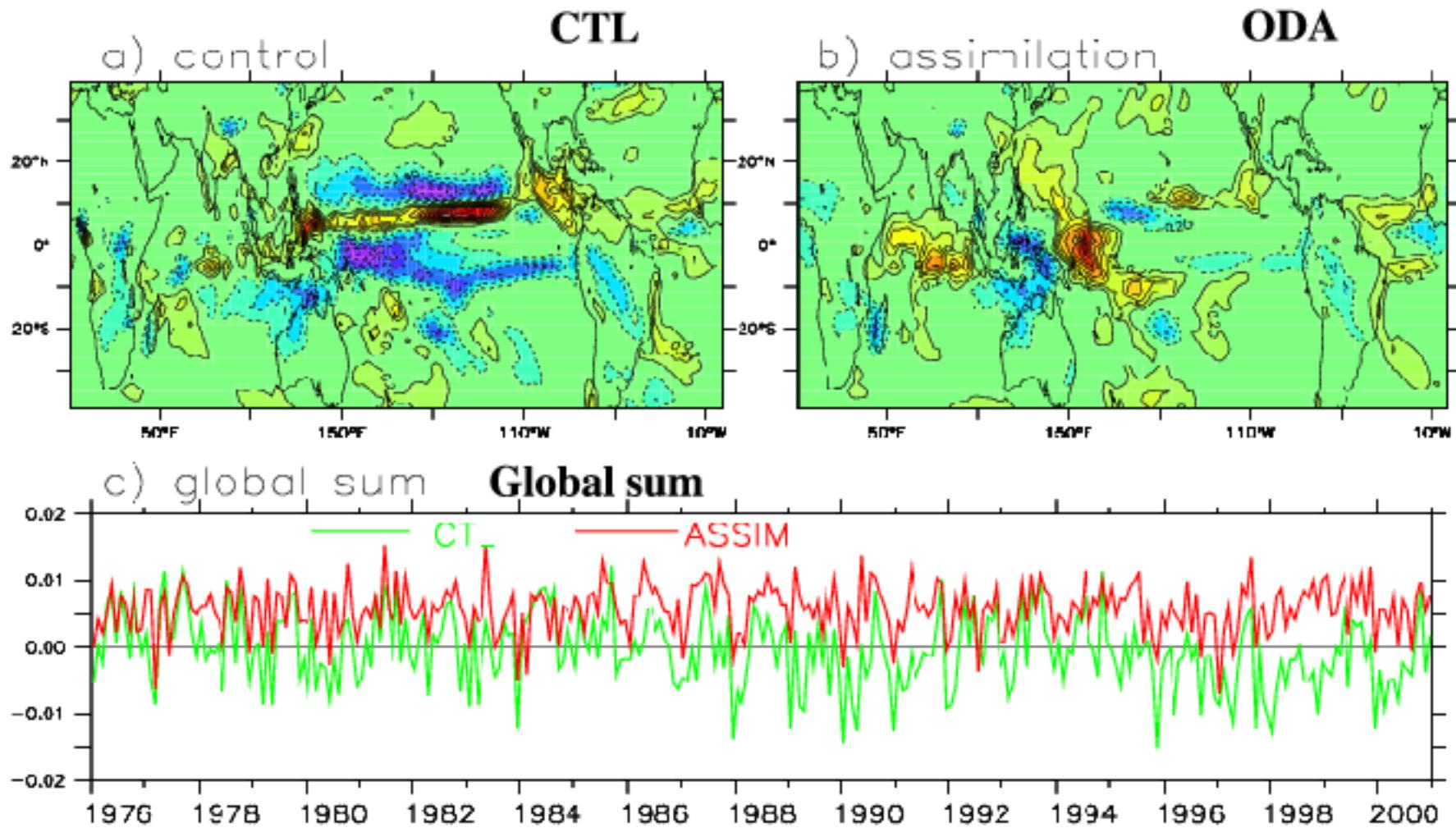


Challenge: 3) Salt 10vr tendency (2000-1990)

Contour interval
= 0.05 (PSU)



Precipitation errors



Remarks

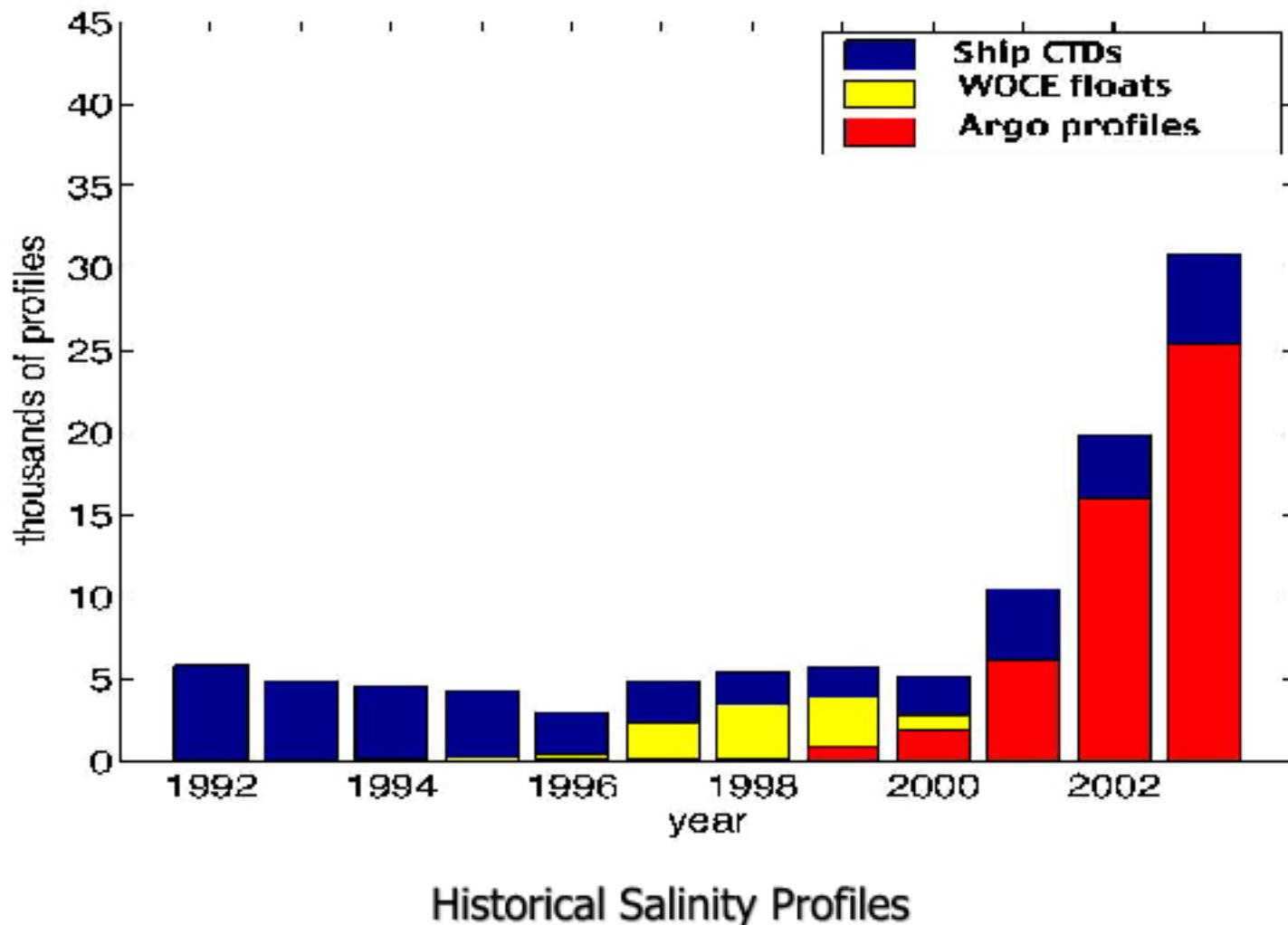
Due to uses of cross-covariance between physical variables, while assimilating obs info the ensemble filter in GFDL's ODA system, to some degree, is able to maintain physical balances in climate evolution, depending on ensemble size, availability of obs ...

Given the 20th century ocean temperature observational network, the ODA process in GFDL's CDA system can retrieve the ocean heat content on basin scales after a 5-year assimilation spin-up.

Based on the temperature observational network, uses of T-S covariance greatly improves the tropics in our experiments. Mid to high latitude improvements were less dramatic.

The north Atlantic is the most challenging area for data assimilation where THC's transport, ice-ocean flux exchange interacting with topography makes difficulties, especially for salt assim; then more source info such as salt obs, sea-surface height may be required to reconstruct the north Atlantic MOC.

Argo and the Salinity Budget



Ongoing experiments for climate detection at GFDL

Idealized experiments to uncover issues and advance the understanding

- § Argo network (temperature and salinity) to estimate north Atlantic MOC (running).
- § Present ocean observational (XBT + Argo) applied to the 21th century
- § Altimetry assimilation (TOPEX,JASON,GRACE).

Real data (profiles+satellite data) to reconstruct the history of climate changes in the 20th century, and continuing to ...

New century for estimating climate states to initialize the SI/decadal forecasts

Challenges

Estimate of north Atlantic MOC by assimilating salt obs (Argo network), satellite measurements (key: tuning assim parameters to maintain most balances)

Real data – Model biases: more source information + multi-model ‘super’-ensemble

- § Altimetry data; Equatorial current measurements from drifting buoy
- § Argo temperature and salinity measurements and the derived temperature-salinity relationship
- § multi-model ‘super-’ensemble filter (Current: atmospheric B-grid and Finite-Volume cores; Soon: mom4+isopycnal ocean model)

Impact of more coupling variable adjustments on ocean states

- § Adjustment of heat/water fluxes using ocean observations within mixing layer
- § Direct constraint on atmospheric boundary by ocean surface observations
- § Direct constraint on weather state from the atmospheric data (using reanalysis, for instance), specially for SI forecasts?

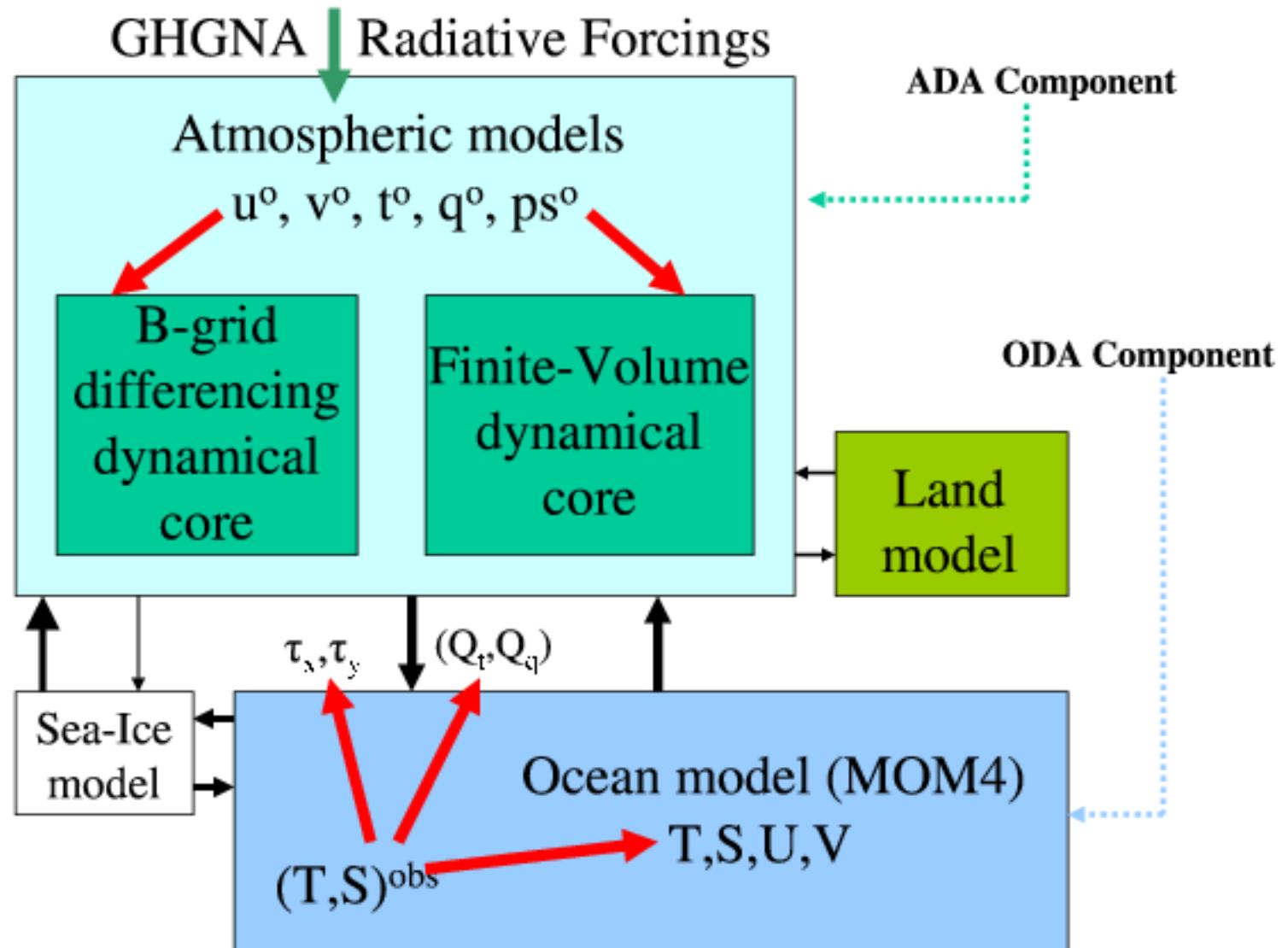
How to increase the observation constraint when ensemble spread is very small (deep water, for instance)?

- § A hybrid filter combining stationary/non-stationary error statistics?
- § A 4-dimensional variational ensemble filtering algorithm in which $B = B_0 + B'(t)$, possible?

Impact of ensemble size on the accuracy of error covariance estimate

- § 24-member system is running on NASA Columbia cluster
(max PEs:2048)
- § Daily atmospheric disturbance as ensemble perturbation

GFDL's Ensemble Data Assimilation System Using Multi- Coupled Climate Models



Long Term Efforts ...

Improve climate variability analysis (Carbon/heat uptake, circulation, ...)

Improve forecast (SI, decadal/multi-decadal) by improving initialization

Detection of climate change

Analysis estimate of variables in sea ice and land model (ice mass, run-off etc., for instance)

Observing system evaluation/design

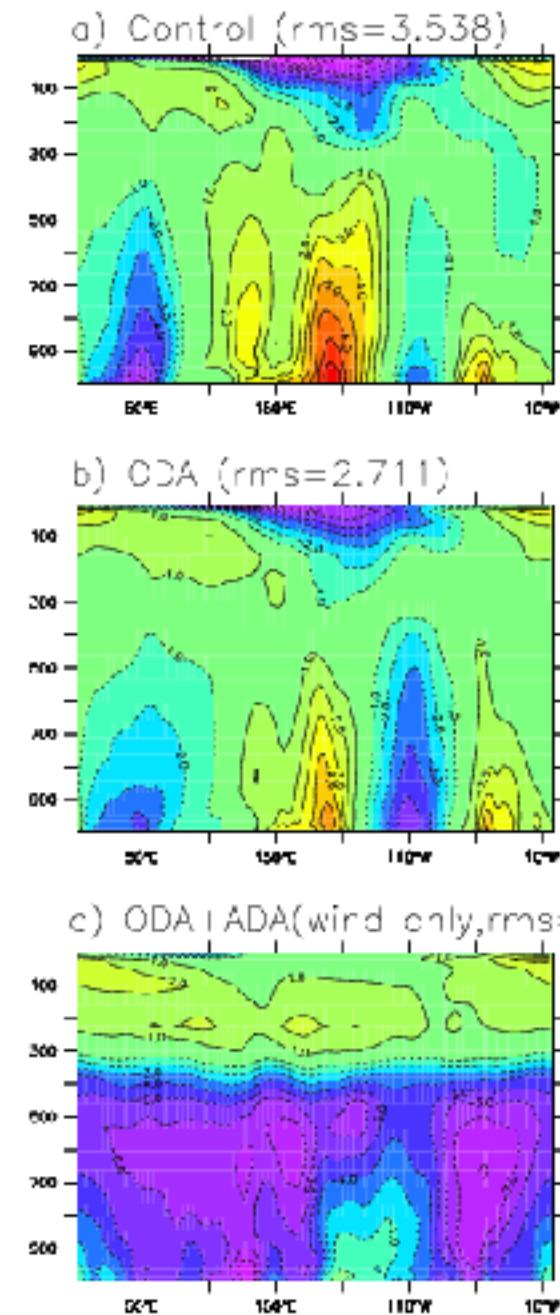
Model evaluation/verification for improving modeling

Model parameter estimation

Thanks to ...

Balaji for supports on domain decomposition and communication, computer resources on Columbia
Andrew for persistent helps on visualization and generous discussions on physical oceanography
Jeff Anderson for helpful discussions on filtering, and early discussions on filtering parallelization
Fengrong, Mike, Hyun-Chul for helps on cm2's configurations; Zhi, Hans for helps on NCO and mppnccombine utilities; Jianjun and Jian for helpful discussions
All GFDL staff for efforts on climate modeling

Atmospheric Temperature Errors at High Latitudes (averaged over $40^{\circ}\text{N} - 90^{\circ}\text{N}$)

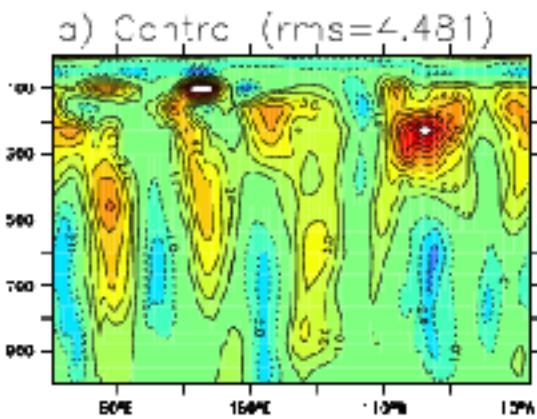


Control (without any data constraint)

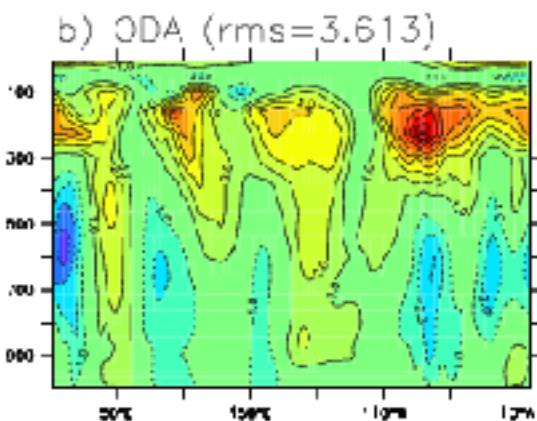
Ocean Data Assimilation (ODA) Only

ODA and Atmosphere Data Assimilation
(ODA+ADA, wind only)

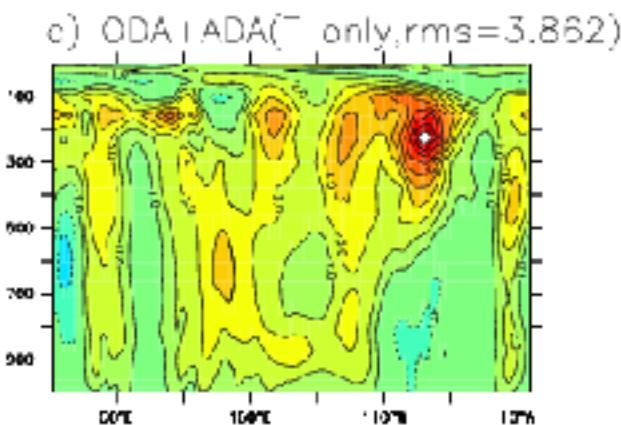
Atmospheric Zonal Wind Errors at Tropics (averaged over 20°S-20°N)



Control (without any data constraint)

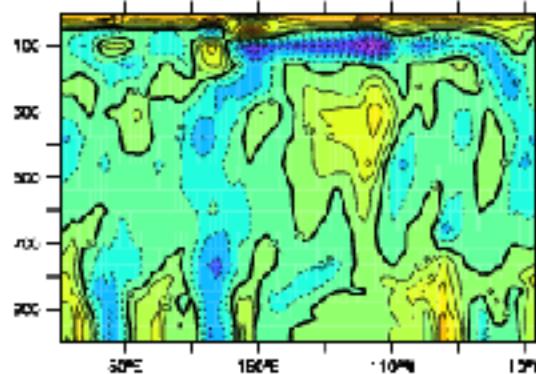


Ocean Data Assimilation (ODA) Only

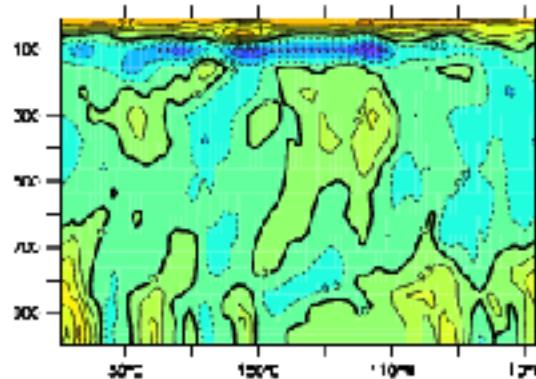


ODA and Atmosphere Data Assimilation
(ODA+ADA, T only)

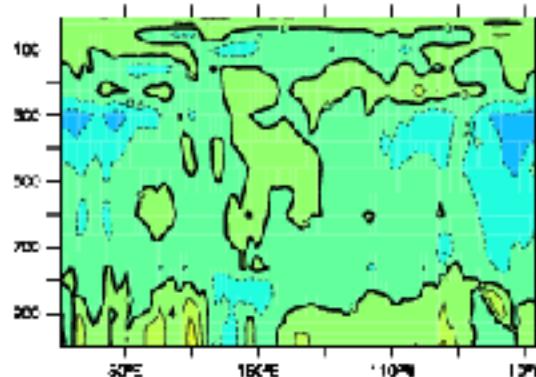
Atmospheric Temperature Errors at Tropics (averaged over 20°S – 20°N)



Control (without any data constraint)

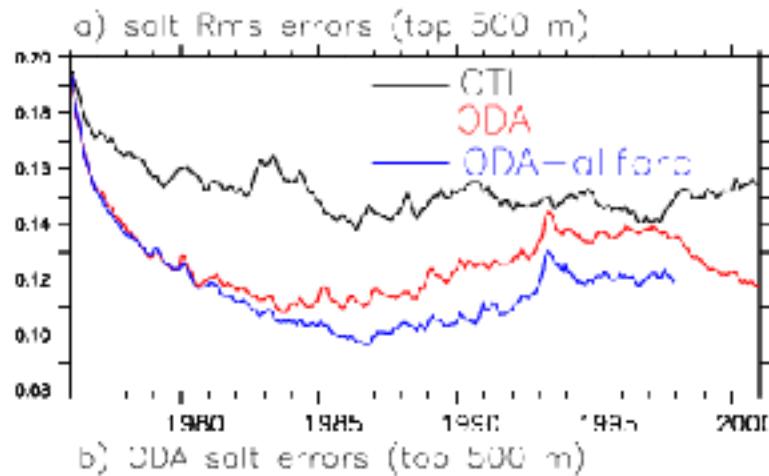


Ocean Data Assimilation (ODA) Only

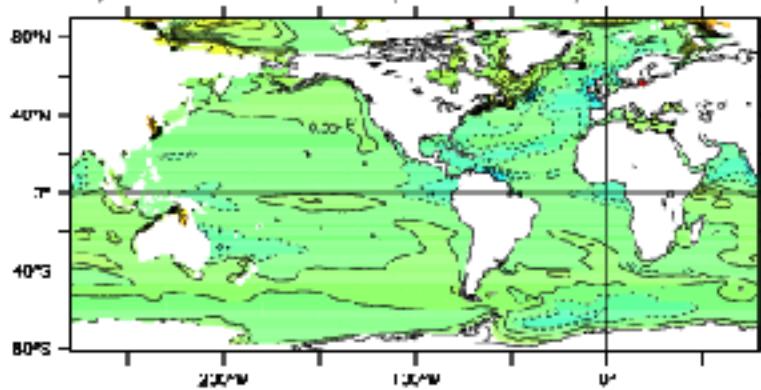


Ocean and Atmosphere Data Assimilation
(ODA+ADA)

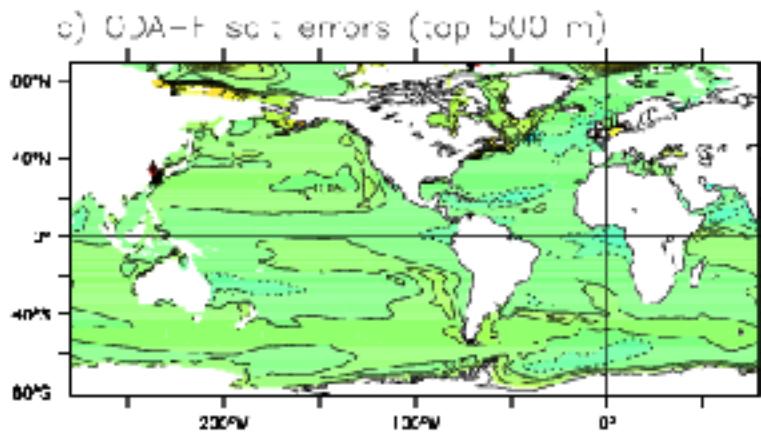
Salinity errors over top 500m



Global Rms error

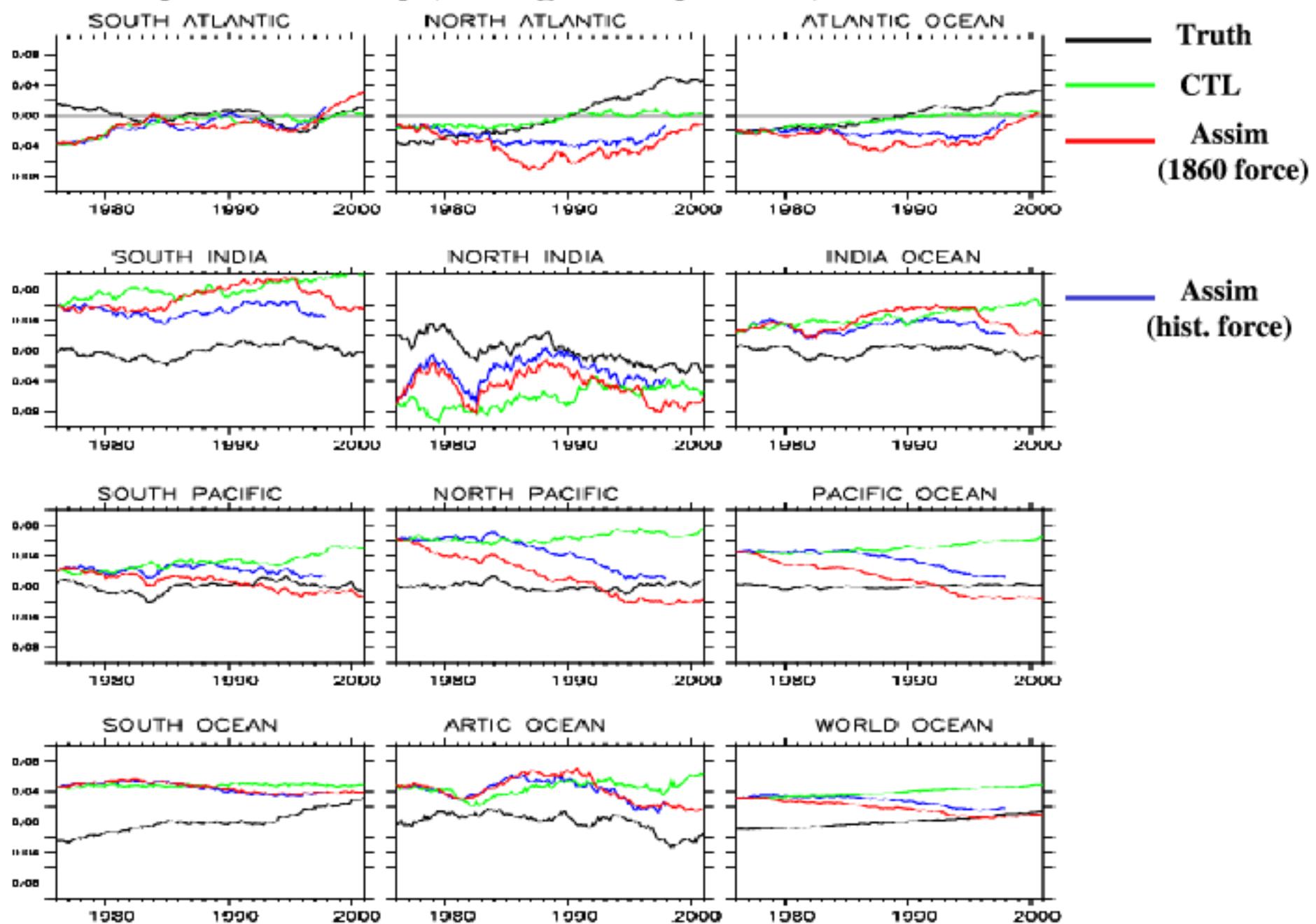


CTL Averaged errors

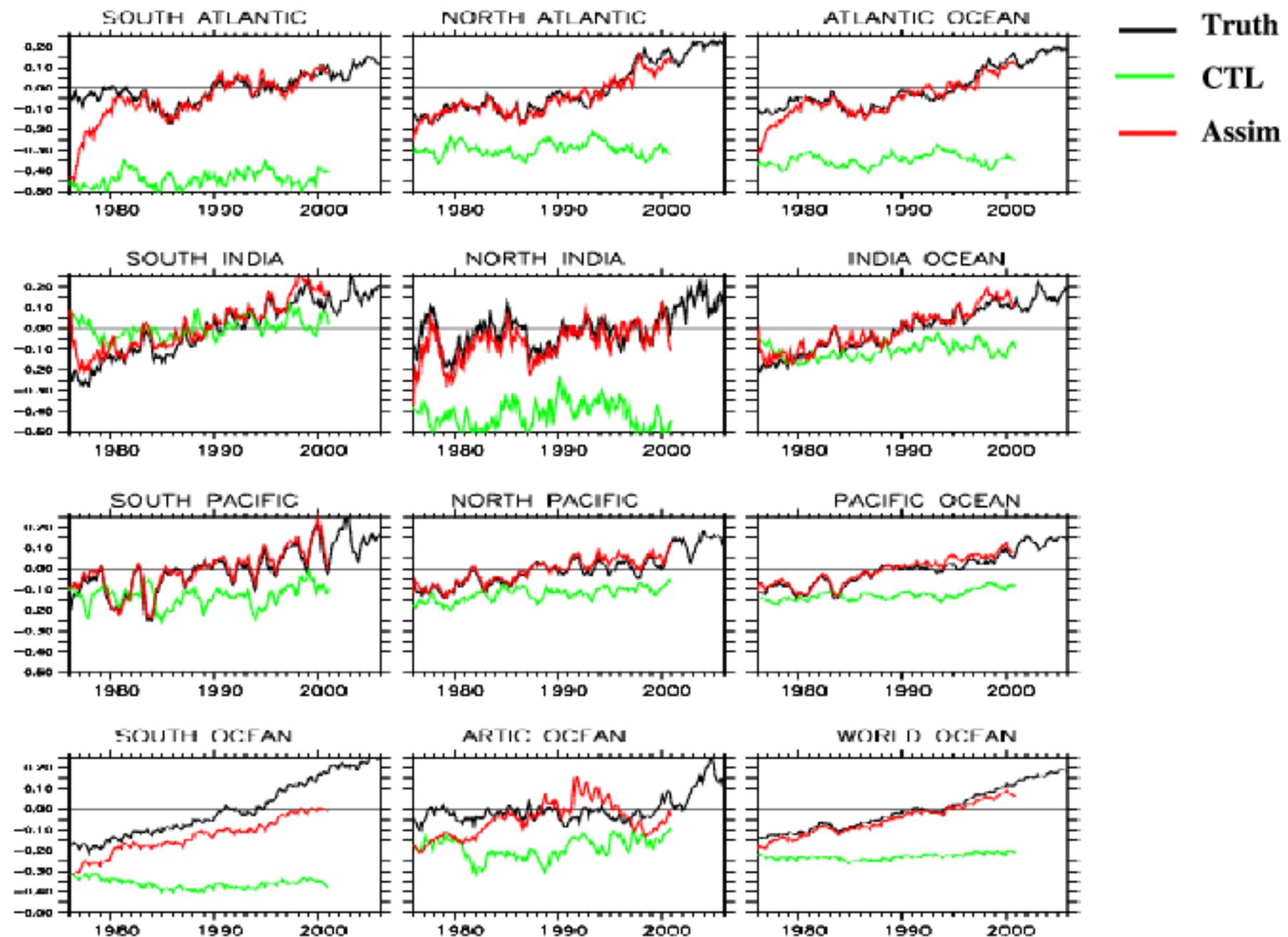


ODA Averaged errors

Top 500 m Salinity (Averaged Temperature) Anomalies



Top 500 m Ocean Heat Content (Averaged Temperature) Anomalies



FOREST (grib2) Ver. 2.79
NOAA/NCEP TRAP
May 7 2005 20:12:06

DEPTH (m) : 0 to 50 (averaged)
TIME : 16-APR-1991 00:00 NOLEAP

